06 THE SERENDIPITY OF MEETING
DR. SWARUP

16 LIFE DEALS A SET OF CARDS AND
YOU HAVE TO DECIDE HOW TO PLAY

26 EXPERIENTIAL LEARNING OF
NETWORKING TECHNOLOGIES
Understanding IP Routing

WHEN INDIA CONNECTED TO THE
GLOBAL CYBER REVOLUTION
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How the Internet has come a long way and changed our lives forever! When launched, it was nothing like the information super highway that we experience now. The internet has become so essential for us now that the world seems to stop without the internet.
In this issue, in a departure from our usual technical contents, we carry a tribute paid by Dr. Hemant Shukla, a famous radio astronomer settled in USA, to another internationally recognized radio astronomer from India Dr. Govind Swarup. In this article titled “The Serendipity of Meeting Dr. Swarup” by Dr. Hemant Shukla, through a series of anecdotes, the author narrates how he came in contact with Dr. Govind Swarup and how his association continued with him until the sad demise of Dr. Govind Swarup. The author recapitulates the moments during his interview as a candidate for admission at NCRA (National Centre for Radio Astronomy) when through a series of questions Dr. Govind Swarup enlightened the author by enlarging the author's bookish knowledge (at that time) to real world knowledge. The author regards Dr. Govind Swarup, a world renowned scientist, as one who is an electrical engineer, a mechanical engineer, a leader, a mentor, a teacher, a student ever willing to learn and above all a great human being with such desirable qualities as humility and respect for other human beings. A fortunate stroke of serendipity led the author's mother to establish lost contact with Ms. Bina Swarup, her classmate and wife of Dr. Govind Swarup. The author expresses his regards for this great scientist and a marvelous human and laments for not being able to attend ninetieth birthday of his 'Guruji' whom he held in high esteem. The depth of author's love and respect for his Guruji is well summed up in the author's statement at the end - "I would die a happy man if I were a fraction of what he was". The editor is reminded of Ekalavya's dedication to his Guru Dronacharya in Hindu mythology Mahabharatha. Both 'Guru' (Dr. Swarup) and his 'Shishya' (the author) are fortunate to have each other in their respective roles.

In the feature article titled “When India Connected to the Global Cyber Revolution” authored by ACC Journal staff writer, the author takes our readers along on the 25 years of historical journey undertaken by India in establishing a countrywide network starting from the creation of Educational Research Network (ERNET). It also records how potential obstacles in this journey were overcome with the cooperation of various governmental agencies and UNDP, as well as top academic institutions in India. One can appreciate the quantum of leap made during this revolution if one were to note that in economical and technical terms what was costing Rs. 25,000 for data transmission at 9600 bits per second for 250 hr duration is available at a fraction of the cost with data rate being as high as 1 Gigabit per second.

The next article titled "Life Deals a Set of Cards and You Have to Decide How to Play" is closely related with the previous one mentioned with the narrative on the cyber revolution in India built through the tireless efforts of Dr. Srinivasan Ramani who was one among those closely involved and significantly contributed in bringing out cyber revolution. He is the only Indian to be inducted into the Hall of Fame of the Internet Society, a global organisation. Dr. Srinivasan Ramani in his exclusive interview for ACC with Mr. Prashanth Hebbar, humbly states that no revolution can be attributed to the efforts of a single individual, be it in the area of health, agriculture, dairy and of course in establishment of cyber infrastructure.

In the continuing series of articles titled "Experiential Learning of Networking Technologies", the author dwells on IP routing, an important requirement in building a computer network.

In closing this editorial, we leave with a sad feeling following untimely death of Dr. Joy A. Thomas, who was a well known expert in the area of Information Theory. Dr. Arogyaswami Paulraj, Professor Emeritus at Stanford University, who has been credited with the invention of wireless communication systems, pays tribute to Dr. Joy A. Thomas with whom he was well acquainted all through the latter's illustrious professional journey.

Dr. N. Rama Murthy
Editor
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The security guard at the front gate of Pune University campus instructed the taxi driver. I looked along from the taxi parked by the curb. The driver walked back to the car.

“He says that the new institute is at the back. It’s under construction,” the driver mumbled under his breath. He pulled the taxi door shut and drove into the campus. I rolled down the window.

The city was cool and fresh from the rain. It was the summer of 1991. The early morning bustle of a strange town always fascinated me. In the subconscious unease of the unknown, it comforted with a warm nostalgic familiarity. The sweepers cleaning the neighborhood. The children waiting for the school bus. People loitering around their favorite breakfast corner. Folks jogging. Fresh vegetables glistening in the first morning light. An old man lost in his cigarette smoke and the morning newspaper. A radio blaring at a distance. People, joyfully greeting each other. Everything seemed nice... We all woke up to the promise of a new day.
Through the unpaved road, we reached the back of the campus. The place was peppered with a few newly built houses and incomplete buildings. This time it was my turn to seek directions. I got out of the car and walked towards a house. Seeing me approach, a man dressed in white walked out of his house and smiled,

“Are you here for the exam?”

“Yes, but —” I could barely speak. I knew the man. I knew him long before I had seen him on TV. He used to provide his expert commentary right before the beginning of my favorite show, Cosmos, by Carl Sagan. The man was well-renowned astronomer Dr. Jayant V. Narlikar.

“—If you continue on this road, you’ll find the registration office. They will further guide you.” He said with a smile. He waved behind us as we drove in that direction.

Back then, the Inter-University Center for Astronomy & Astrophysics (IUCAA) and the National Center for Radio Astronomy (NCRA) were relatively new institutes. They conducted a joint entrance examination for students inspired and eager to pursue a career in the field. I was very interested in radio astronomy. I was deeply fascinated by the idea of ‘seeing’ the invisible universe. I still am. To my surprise, there were too many of us. I had just finished my astronomy summer school at the Indian Institute of Science, where I had the privilege of studying under the leading scientists. I was brimming with immature confidence.

At the summer school, I had come across an introductory brochure of NCRA. In which I had learned that NCRA was building the world’s largest radio telescope array. It was called the Giant Meter-wave Radio Telescope (GMRT). The meter-wave part meant that the telescope would search for extremely weak light coming from very distant objects (protogalaxies and protoclusters) that were in their early stages of the formation when the universe was very young. I was hooked for life.

The format of the admissions process was designed to eliminate in stages through written exams, interviews, and then the final interview.

I, luckily, passed the hurdles and reached the last interview. The interview was in a small office with a large window. I was ushered into the room. To my left wall was a large whiteboard. And huddled in the corner of the opposite wall by the window were four smiling gentlemen. One of them, whom I had already met, was Dr. Narlikar. To his left was another gentleman whose big, happy smile put me at ease right away. I gathered that he was from the NCRA part of the admissions committee. And to either side sat the other two men. I want to say that one of them was Dr. Kembhavi, but my memory is fuzzy on that. I nervously stood by the whiteboard. I had instinctively picked up the marker and was ready to write. After a brief introduction, the gentleman with a big smile started asking personal questions, mostly about my hometown.

He seemed to know the place quite well. He then explained that a part of his family was from my hometown. And once my nerves were calm, the ‘grilling’ began.

During one of my trips to India in the late nineties, Dr. Swarup invited me to visit GMRT. Since the interview, this was the first time I was meeting him. At NCRA, I could tell that he was eager to show me his labor of love. He accompanied me to the telescope location, about 80 km from NCRA.

At some point through the barrage of questions, the discussion switched to the cosmic background radiation (CMB), the embers of the hot origins of the universe. These were pre COBE times, but the consensus was that CMB had a blackbody spectral signature. I had sketched the Planck’s blackbody curve on the board. That’s when the gentleman from NCRA, with the big smile, took charge of the discussion. He honed in on the y-axis of the plot that I had sketched.

“What is on the y-axis?” He asked.


“Good. And what are the units?”

“Ah,” I fumbled and then wrote the units somewhat apprehensively.

More questions followed; precise and expertly designed questions, just to nudge an inquisitive mind into self-discovering deeper relationships between physical quantities, often taken for granted in textbooks. Led by hand through these equations, I suddenly ‘discovered’ that within the limiting case of the Planck’s law, the power from a distant object measured by a radio telescope was the same as its temperature. The radio telescope was a thermometer!

My sudden joy of discovery reflected brightly on the face of Dr. Govind Swarup. He had made me think differently about an issue that I thought I had understood. And this is how he made his first and lasting impact on me. In just a brief discussion, he taught me that the foundation of science is to never stop asking and investigating. There’s often more than meets the eye. Just with his few well-poised questions, he had elevated me from the books to the inextricably linked real world of the actual implementation.

Upon my return from Pune, one day, when my mom...
was busy with her daily chores, I followed her around the house, sharing with her my experience from the summer school and Pune. I excitedly mentioned how this one man who also asked me questions about my hometown had dazzled me by teaching me new ways of scientific inquiry. She nodded and left the room. A few minutes later, she returned with an old photograph of a young man and a woman.

“Was that professor this man?” She asked, handing me the picture.

I took the picture, a very young Dr. Swarup was smiling back at me.

“Yes!” I exclaimed, “How did--?”

“--Are you sure?”

“Yes, this is him... his younger self,” I reassured.

My mom was ecstatic. The lady in the photograph was Mrs. Bina Swarup, my mom’s long lost childhood friend.

And that’s how we all got reconnected with Dr. Swarup and Mrs. Swarup.

I did not get admitted to NCRA. I moved to the US to continue my education in radio astronomy and physics. Throughout the years, I stayed connected with Dr. Swarup.

During one of my trips to India in the late nineties, Dr. Swarup invited me to visit GMRT. Since the interview, this was the first time I was meeting him. At NCRA, I could tell that he was eager to show me his labor of love. He accompanied me to the telescope location, about 80 km from NCRA.

We survived the bumpy car ride and reached the remote site. At that moment, there were roughly thirty telescopes. Each was 45 meters in diameter. Up close, the telescopes were massive. The telescopes were arranged in a Y-shape across a 25 km area. The innovative design by Dr. Swarup had made GMRT one of the leading telescopes in meter-wave astronomy in the world. He told me that since the observed wavelengths were long, he designed the mesh-based dishes (radio antenna) instead of filled ones. This way, he saved the cost of metal per dish, and eventually, the total cost of the telescope.

The local village juxtaposed against the world’s largest telescope was a sight right out of India. I was working at Caltech in those days and had access to a similar, but smaller array right outside my office. I was quite impressed by GMRT.

At the young age of 67, Dr. Swarup’s zeal for science, especially radio astronomy, was contagious and inspiring. I stayed with him for the next few days. And just like the interview, this time, I got a priceless crash course in radio techniques from a world-renowned scientist who never made you think that he was one by his sheer humility and grace. Dr. Swarup was not only a scientist; he was an electrical engineer, a mechanical engineer, a leader, a mentor, a teacher, and forever willing to learn. He was a complete scientist. In today’s world of suffocating specialization, that was such a breath of fresh air.

Besides his friendly and kind demeanor, Dr. Swarup was blunt when needed. He did not like it when, out of tradition, to greet him, I used to touch his feet. And he did not like me calling him Dr. Swarup. Reluctantly though, I was able to forego the feet touching. But he is forever Dr. Swarup to me.

He tried to recruit me a few times, but I was happy far away. Again he never minced his words and with a laugh once said, “Raju ban gaya gentleman!” (Local lad has become a gentleman). Even his insults were inspiring.

We stayed in regular touch. Whenever I needed advice, he was available. When he learned that I was planning a brief trip to India, he invited me to GMRT again. I happily took the offer. I stayed over in Pune for a couple of days. These trips required giving a colloquium talk. Back then, I was working on a Dark Energy project and had enough material to share. After the talk, he handed me over to the other professors and suggested a time when I stop by his office and retire for the evening and dinner.

“I have something to show you. Stop by at 4:00, sharp,” he added.

I knocked on his door at 4:00, sharp. He invited me in. He seemed to be in a thoughtful mood. I assumed he was preoccupied.

But he turned to me and said, “Good talk. I have a question. Why at 1.8 z?”

I knew what he was asking. He was curious why Dark Energy suddenly seems to accelerate the universe after a random time (or z for redshift). I walked up to the board in his office, which was already cluttered with equations, and in the corner sketched the energy density vs. time (redshift) plot. It was quite a deja vu moment.

The y-axis of the plot was the energy density of the universe. I did not write the units. Now I was old enough to know that units were irrelevant. You could set them to whatever value that suited your needs. And the x-axis was time since the big bang. Then I drew the matter density. A curve starting high close to the origin and then decreasing as the time on the x-axis increased. Next, I drew a horizontal line parallel to the x-axis. And where the line crossed over the curve, I marked that point as 1.8 z. I did not say a word and turned to explain. I saw the familiar wide smile and a gleam in his eyes. I knew immediately that he understood what I wanted to say.

“This is one of the best explanations I have seen. OK!” He said.
I was proud to have shared my knowledge with him for a change.

Dr. Swarup had a way of returning to the main topic.

“Coming back, here’s something I wanted to show you.” He said as he took out a small black diary.

“Do you remember your first interview with us?” This must have been more than a decade now.

“Yes,” I said.

“I took some notes that day. Read this.” He handed me the diary. It read (am paraphrasing) – he’d become an astronomer someday.

I was dumbfounded. I had no idea how to respond to this. I stood there quietly holding the diary. He then took out another slightly larger diary and opened it. This was his autograph collection book. He showed me many signatures of people that I knew. I recall seeing S. Chandrasekhar’s signature. Then he handed me a pen and asked me to sign the book. I couldn’t. Instinctively, I refused.

“Rubbish. Why not? This is my book.” He exclaimed.

“But... this has Chandra and so many others... I don’t belong here.” I grumbled.

“Just sign it.”

So I did.

This was his way of encouragement and guidance. He made you feel welcomed.

I met Dr. Swarup a couple of more times since. The last time I met him in person was when I was on a historical trip across India with my mom. We decided to stop over in Pune and meet with the Swarup’s. Dr. Swarup suggested that now I know enough radio astronomy to show my mom around GMRT. I did. My mom was quite impressed by the telescopes. During our stay in Pune, we tried all kinds of amazing street food with Dr. and Mrs. Swarup and had a blast.

In 2008, after many discussions, Dr. Swarup and I agreed to work on a long-overdue collaboration. He wanted to do something weighty, something exciting, or not at all. I was on the same page.

“Read up on WMAP Cold Spot and then we’ll talk,” Dr. Swarup directed.

In short, there’s a region of the sky, about 5 degrees (10 full moons) in size, which breaks away from the norm. It appears emptier than it should be. A survey of the region using radio telescopes indicated the same. This result had caught Dr. Swarup’s attention.

There were a few tentative explanations proposed in the scientific literature, including that it could be some form of data aberration. I raised this issue with Dr. Swarup, and his response was, and I paraphrase, “I did not build a telescope to use statistics to find my answers. Let’s go observe the thing and find it for ourselves.”

Using GMRT, we were able to corroborate the previous observational results. Later, the results from the Planck satellite further confirmed the existence of the cold spot. In other words, the mystery remains. But despite the best of our efforts, we were unable to complete the project to the extent that we had originally discussed and planned. This remained a point of our mutual dissatisfaction.

Time flew by, and before we could revisit our project, I was invited for the 90th birthday of Dr. Swarup that was celebrated by NCRA. Sadly, I was unable to attend. I decided to send my regards through flowers and a brief note entitled – The Serendipity Of Meeting Dr. Swarup. And not until a few months ago, to my horror, I discovered that the article got lost in the mail and never reached him. I started to rewrite this.

Today I woke up to an ominous morning. The sky was bright red due to the smoke from the fires all around the San Francisco Bay Area. That’s when the news arrived, my teacher, my mentor, my advisor, my guru ji Dr. Swarup had passed away.

The news was sudden and unexpected. It hit hard. I was already fondly reliving the past while rewriting this note. The loss became very personal and palpable.

I realize that now no one would be able to fill those shoes. But we all could aspire to walk the path defined by Dr. Swarup’s unbridled curiosity, passion for lifelong learning, taking on and completing larger than life projects, and most importantly, humility and respect for others. Dr. Swarup was a great scientist, but above all, he was a marvelous human. I’d die a happy man if I were a fraction of what he was.

It will forever remain a source of deep sadness for me that Dr. Swarup did not read this note that I wrote for him. I will deeply miss him all my life.
WHEN INDIA CONNECTED TO THE GLOBAL CYBER REVOLUTION

ACC JOURNAL STAFF WRITER

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How the Internet has come a long way and changed our lives forever! When launched, it was nothing like the information super highway that we experience now. The internet has become so essential to us now that the world seems to stop without the internet. We need it to pay bills at kirana shops, to check our bank accounts, send and receive mails, watch movies and many things more.

When the Internet was launched in India in 1995, it was a groundbreaking moment. The country had opened the flood gates of economy just four years earlier and there was hope and trepidation all around. But there was definitely an excitement for what was to come for an economy that had been put in chains for over 40 years.

It has been 25 long years since the internet, which is a behemoth now, started its baby steps in a vast and diverse country like ours.

As if to signify the changes and freedom it would bring us, the internet was formally launched on the Independence Day, August 15, 1995. Videsh Sanchar Nigam Limited (VSNL) formally made it available to the public on that day.

The Internet moved quite swiftly from boxy, bulky desktops to cellphones in our palms. Anything and everything from anywhere around the world seems available to us at the touch of a button, and that too within a few seconds. The social changes that have occurred, solely because of the internet, are mind boggling.

Who would have thought just 25 years ago that you could pay all your utility bills sitting at the comfort of your home? Or fight for a cause that is close to your heart by sending in tweets or putting up Facebook posts. You can have exchange tweets with anyone across the globe. Whether that person is a celebrity or a commoner. In fact, I feel, commoner is a misnomer now. The masses are not faceless anymore. They have a voice, an identity and their rightful place under the sun, because of the internet.

In fact, Internet already existed in India since 1986. Then, it was in the form of Educational Research Network or ERNET. It was meant only for educational and research institutes and communities. ERNET was the joint undertaking of the Department of Electronics (DoE) of the Government of India, and the United Nations Development Program (UNDP).

ERNET was launched at a time when the internet was just emerging out of labs in the US and a few places in Europe. The idea was to get the technology to India. Eight institutions were chosen for the task. They were the National Centre for Software Technology (NCST) in Mumbai, which is now known as the Centre for Development of Advanced Computing, the department of electronics in the Union government, the Indian Institute of Science (IISc), Bangalore, and five IITs of Madras, Bombay, Delhi, Kanpur and Kharagpur.

Srinivasan Ramani, one of the eight project coordinators, was one of the key persons to get the internet to the country. As early as 1983, he had proposed that an Indian academic network should be created. For his pioneering work, Ramani was inducted into the Internet Hall of Fame in 2014.

In an article on the Asia Internet History Projects, Ramani recalls how ERNET started UUCP or Unix to Unix Copy Protocol email exchanges between NCST and IIT, Bombay in 1986–87. It also established TCP/IP connectivity between major cities in 1988–89.

UUCP allowed systems to dial each other to send emails and information. It also enabled transfer of files from one system to another. The project soon developed into an autonomous ERNET India Society with over 600 institutions across the country.

Ramani writes in IBNLIVE.com that the Advanced Research Projects Agency (ARPA) had funded the creation of the pioneering network, ARPANET. CMU was a node on this network and so I became one of the first few hundred users in the world of computer networks and email.

One of the considerations behind the creation of ARPANET had been the fact that packet switching networks are resilient against failure of equipment and communication links. That meant that packet switching does not need a perfect communication system, as long as there are communication links even if they are noisy (error-prone). It would make up for weaknesses of the underlying communication network. Secondly,
there was the magic of message switching. You don’t have to suspend what you are doing and run to your computer terminal the moment an email arrives as you rush to the phone when you receive a phone call. Email gets stored somewhere and waits for you to log in at your convenience. Packet switching nodes, basically what we now call routers, handle noisy communication links well. If an information packet does not get through properly, the receiving end complains to the sending node that packet number x was not received. The sending node makes up by sending a copy of x. I recognised that a developing country like India needed this technology very badly; there was no doubt about noise on our communication links. Our communication network was growing day by day. As new communication links come up, it would be easy for routers to recognise the new resources automatically and start using them. The routers resemble “intelligent” controllers in their ability to do the right thing at the right time and to coordinate with their neighbours, without obeying a master in an engineering bureaucracy.

Ramani writes saying I have used the phrase “ERNET Partners” so far to mean only the eight institutions that had started the ERNET project as a group. However, as they started linking up, it was time to share infrastructure with other academic and research institutions. The International Centre for Astronomy and Astrophysics (IUCAA) in Pune was one of the new institutions to connect to ERNET. TIFR followed very quickly and more and more institutions started connecting up. At the peak, dial-up links shot up to a few hundred all over India. Slowly some of them also acquired leased lines, and went on to support dial-up subscribers in their own cities and their neighbourhoods.

The rise of the Internet in India was more or less in the same period during which the Indian software industry pioneers were making their mark. The government saw the potential of the software industry. Mr. N. Vittal, then Secretary to Government at the DoE, and a few other administrators were very highly supportive of both developments. A piquant situation arose when the fledgling software industry badly needed email and there were no Internet Service Providers (ISPs), public or private. ERNET informally started giving email facilities to the software companies. A wrong person above us could have put a stop to this very quickly saying we had no right to do so as we were only an academic network. Instead, Vittal was supportive. DoE was funding the ERNET, and was at the same time carrying the responsibility of making the software industry grow. So, when we briefed him with some timidity about ERNET giving support to software companies, he made it clear that it was the right thing to do. We were afraid of trouble with telecom department. These were very tough days; if multiple landlines were to be terminated at an institution, that institution could not create a network out of them. They were to be used only as point to point lines. At the beginning, when the hub served only as an email hub, we had a fig leaf - there was no level 2 or level 3 connectivity between the connected institutions. Instead there was only a store-forward message system named an email relay computer connecting them. This was dangerous - the whim and fancy of one officer could have pulled the carpet from under us. Vittal reassured us; the government had decided to give priority to the growth of the software industry, and this industry was vociferously in need of the Internet.

Ramani writes that the entry of VSNL, which was then a public sector company, as a provider of Internet Gateway Service in 1995 was a turning point for software companies and other non-academic users in India. The setting up of specialised Internet access facilities by the Software Technology Parks under the DoE was another major development. This was followed up in 1998 with the Government announcing a policy that allowed for setting up of private ISPs. A committee headed by the then Chief Scientific Advisor to the Prime Minister had looked into certain technical issues preparatory to the decision to allow private ISPs. The Secretary to Government, DoE, had asked me to work with this Committee. So, I had the pleasure of working with a charismatic leader over a few Committee meet-

Who would have thought just 25 years ago that you could pay all your utility bills sitting at the comfort of your home? Or fight for a cause that is close to your heart by sending in tweets or putting up Facebook posts. You can have exchange tweets with anyone across the globe. Whether that person is a celebrity or a commoner. In fact, I feel, commoner is a misnomer now. The masses are not faceless anymore. They have a voice, an identity and their rightful place under the sun, because of the internet.
ings - Abdul Kalam. His keen interest in the technology of the Internet was an inspiration.

There was also the NICNet which started in 1988. The National Informatics Centre managed it to improve the communication between different government institutions.

Then came the formal launch for the general public in 1995. But bringing internet to the country was not easy and smooth. There was a lot of criticism and negative publicity.

But tech enthusiasts like Kanakasabapathy Pandyan, VSNL former chairman Brijendra K. Syngal, VSNL technology director Amitabh Kumar and leaders from the corporate world ensured that the internet reached the Indian shores.

Syngal says that VSNL started providing digital connectivity to some software companies at 64kbps speed since 1992. But they wanted to offer it to the common people too. Also, the Telecom Commission was pushing VSNL to roll out commercial internet services. In 1994, the public internet service existed only in Japan and Hong Kong, while Singapore was still experimenting with the idea.

In his book Telecom Man, Syngal says the key component was connecting to an internet service provider outside India. VSNL could get to Australia, Japan, Hong Kong, the US and the UK. It zeroed in on 128 kbps lines to these countries and simultaneously started setting up the hardware.

Beta testing was conducted in July 1995. Citizens like Vijay Mukhi, Miheer Mafatlal and actor Shammi Kapoor, who had formed the Internet Users Club of India, signed up informally to use the service. Syngal writes that these people were happy to be around when VSNL launched the service. They bounced off ideas and suggested ways to make the service more user-friendly.

Even China did not have a commercial internet service then. In fact, the Chinese vice-minister visited VSNL in 1996 “to learn the tricks of the trade”, Syngal writes in his book.

Despite initial doubts, the internet was a huge success after it was launched. Within six months, the telecom provider had 10,000 users. The initial launch was in the four metros of Delhi, Mumbai, Chennai and Kolkata, and the precursor to India’s jump to commercial Internet was the Educational and Research Network (ERNet) which helped the technologists and technocrats in the government understand the nature of a country-wide network which will connect to the rest of the world with almost seamless access to anyone anywhere. The story of how ERNET came about is interesting.

Dr Srinivasan Ramani, who was then with the National Center for Software Technology (NCST) recalls how after his return from the US where he was extensively exposed to the ARPANet, the precursor to the Internet, the institute bought Unix software and realized that they already had the networking software, the same one which powered the ARPANet. “That gave us immense confidence to say that we can build networks in India,” Says Dr Ramani.

A handful of engineers in NCST had already built a network between TIFR and Victoria Jubilee Technical Institute where they held software development course. And it hit upon them that they could build a network linking all the educational institutions in India – a model similar to that in the US where Internet took shape with a network that linked up all universities. Dr Ramani and team proposed to the government that such a network connecting all educational institution will be equally owned by all the participating institutions. Our proposal was accepted and soon IITs joined, then leading universities, research groups and social groups joined the network. That was perhaps the initial seeds of a network and computerization revolution in India.

See Interview with Dr Srinivasan Ramani for more details.
then Pune. Bangalore, the Tech City that is home to hundreds, if not thousands, of information technology companies got the internet by the end of that year.

The rates were exorbitant. It was 25,000 rupees for a 250-hour connection at 9.6 kbps speed.

Yes, that is right. The speed was just 9.6 kbps. Now, that we use internet at speeds of up to 1 gbps, it is like a race between a turtle and a Ferrari.

Then, the Internet had to be accessed using a device called Modem. It is a short form for modulator-demodulator. The machine enabled the computer to transmit data over telephone cables by converting analog signals into digital.

Working with a modem was not easy. It would whizz and whirr before connecting to the telephone line. Also, one had to dial repeatedly before getting the connection. And, there was no guarantee that the connection would stay put as you were surfing the internet.

The Gateway Internet Access Service by VSNL offered two types of internet connection based on the type of users. It distinguished them as ‘shell’ and ‘transmission’ controlled accounts. The first for individuals and students with a nominal tariff plan. These accounts provided “text and text-related information on screen but not graphics or images.” Users could download graphic files onto their computers though.

Transmission-controlled account allowed a simultaneous viewing of both text as well as graphics and images without the need to download the files.

The late arrival of the internet had some advantages. By the time it hit the Indian shores, the World Wide Web had matured. There was already web browsers like Mosaic and Netscape Navigator to be used. Both these browsers are now part of the internet blackhole where millions of such ventures have vanished into.

A year after the internet was launched, the software services lobbying group Nasscom set up a booth for VSNL at the Nehru Centre in Mumbai to demonstrate what the Internet could do.

Writing about the challenges faced, Syngal says Nasscom chief Dewang Mehta came up to him and said, ‘Mr. Syngal, this is the opportunity of a lifetime. We need to demonstrate what the internet is all about. Can you get a couple of 2 mbps lines into Nehru Centre?’

That was not easy. But Syngal said to his people: ‘This is a god sent opportunity. We have mastered the art of providing digital connectivity. Let’s show the world what we can do.’

So VSNL had a booth at the Nehru Centre where they would give live demonstrations of downloads. The excitement among the young people was tremendous. There would be a stampede every day.

R.K. Takkar, chairman of the Telecom Commission, heard about it and came down to see it. The staff asked Syngal whether they should clear the crowd around the booth for him. Syngal told them ‘No, let him wade through the crowd. Let him see the euphoria among the youth.’ He was quite amazed by what he saw.

Syngal writes that someone remarked that VSNL did not need to rent a crowd – the crowds came like bees homing into their hives. Such was the euphoria.

After that VSNL never looked back and continued to provide wider connectivity. It ultimately led to private sector participation.

Here are some more important milestones in the history of Internet. Some of them are good, some are bad. But they are milestones all the same.

A year after the Internet was launched, Rediff.com opened India’s first cyber cafe in Mumbai. In 1997, ICICI Bank started online banking. Integrated Services Digital Network (ISDN) access, which offered better internet speeds, was also introduced that year.

The new millennium started with the dotcom bubble burst. It took another two years for airlines to launch the online ticketing system.

It was a watershed moment when the broadband was introduced in 2004. The government formulated a broadband policy. It defined broadband as “an always-on Internet connection with download speed of
The social networking phenomenon started in India in 2005, while Orkut and Facebook came a year after. In 2008, 2G spectrum was allocated, followed by 3G a year after. WiMax also was auctioned in 2010.

In 2010, the government auctioned 4G spectrum which gave a big boost to the growth of internet across the country. It allowed people to stay connected, always. We now can access the internet at homes, offices, railway stations, markets or for that matter almost anywhere.

With the opening up of the internet has come the necessity to regulate it.

One should know that Indian citizens do not enjoy absolute right of freedom of speech and expression as there are certain reasonable restrictions under Article 19(2) of the Constitution. Regulations are necessary to ensure that the content featured on online streaming platforms remains within the scope of Article 19(2) of the Constitution.

Movies are certified by the Central Board of Film Certification (CBFC) and governed by the Cinematograph Act. Such certification is also necessary for movies streamed by online platforms.

As per the IT Act, citizens can seek legal remedies if the content contravenes any of the provisions of the act.

Sections 1 and 75 of the IT act collectively make the legislation applicable to any person of any nationality anywhere in the world. This is as long as such services are felt on computers, computer systems or computer networks physically located in India.

For better or worse, the Internet is beyond any regulation. That is because it allows service providers, content providers and consumers to be at different jurisdictions and geographical locations.

Also, it is difficult to regulate the content. That is because what is inappropriate for someone may be perfectly acceptable to another group. It is up to the people to decide they want to see, hear or read a particular thing on the internet.

But more and more countries are realising the need to regulate the Internet within their physical boundaries. Russia and China already have laws which state that the content should be in compliance with the local laws.

The government needs to ensure that online streaming platforms work within the boundaries of local laws. The government should also set parameters for monitoring. Streaming platforms should form a body that goes beyond boundaries and formulate a self code of conduct.

As far technologies and media are concerned, we use dial-up, coaxial cables, ethernet, ISDN, 3G and 4G to access the internet. A study estimates the number of internet users in the country at around 63 crore people. Though some disagree with the number, it is certain that the country has a very large number of people using the internet. Only China has more number of subscribers than us in the world.

The internet has changed the way the business is conducted. Many online-only companies have been threatening to outpace or already overshadowed traditional brick-and-mortar establishments. The country has seen a tremendous growth because of the internet. There seems to be no boundaries for possibilities.

Syngal puts it succinctly when he says, “If you compare the GDP at that point in 1995 and what it is today, all this couldn’t have been possible without digital connectivity and the internet... These 25 years will be a speck in the near future.”

Indeed it is.
LIFE DEALS A SET OF CARDS AND YOU HAVE TO DECIDE HOW TO PLAY

INTERVIEW WITH DR. SRINIVASAN RAMANI BY PRASHANTH HEBBAR

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It’s been 25 years since India connected to the Internet. It is therefore apt to be speaking with the person who propelled the engine which eventually brought Internet connectivity to India and foresaw revolutions in data communications that would change the lives of the Indian industry, as well as the common man. He was a pioneer who foresaw the utility of satellite communications, especially the LEO Satcom, in connecting the remote parts of a developing country. Within a decade of his visionary paper, he saw his ideas being implemented. He later worked with ISRO, helping them build a data communication infrastructure into their APPLE satellite. He also planned and oversaw the rollout of the first countrywide data network, based on TCP/IP, which connected to the Internet and put India on the digital world map.

Well, dear readers, we are talking about Dr. Srinivasan Ramani - the only Indian who has been inducted into the Internet Hall of Fame by the Internet Society. Dr. Ramani also started the first ever post-graduate computer science course for young engineers to skill up on the much-required software. Excerpts of an interview by Prashanth Hebbar.

Dr. Ramani: Perhaps to give me more credit, you said that I was the person who made it all happen. I disagree with that. Nothing is ever done by one person. I look upon life as a series of revolutions. In 1947, when India became independent, people’s life expectancy was wanting. They did not live beyond approximately 45 years or so; life was very short. But then, the good revolution, that is the health revolution, occurred in India. Now,
we live about double the time of what we used to live in the old days. Green Revolution, White Revolution, we have seen so many. Without some of them, we would not be alive today. The Internet Revolution was also one of them.

The communications revolution I should say. It is not just the Internet, but also the fiber optic cables and the satellites. Technology for the telephone exchanges. Every one of them has been a revolution. Young engineers today are enjoying the solar power revolution. And we will very soon enjoy the electric car revolution. Now if you look at any one these revolutions, probably tens of thousands of engineers have worked on each one of them.

So, I should say that the telecom revolution without the fiber optics would not be here today. The Internet would not be what it is. Satellites were great, but the fiber optics give you a bandwidth which is far more amazing as compared to the satellites. So lots of things have happened. And in my work, I was just one of the 8 coordinators from 8 institutions. In the 1980s, there was the Department of Electronics and the Department of Posts and Telegraphs, the IITs, IISc, TIFR and my institute which was the National Center for Software Technology. Now we are part of CDAC (Center for Development of Advanced Computing). In all these eight institutions, there were coordinators. I was one of them.

We had an advantage. We belonged to Computer Science Departments which had been around 10 years before the Internet revolution came, so we had the right computer and the right software in the most important city of [Bombay] Mumbai. The City of [Bombay] Mumbai had excellent connectivity with the world, so we could connect with others easily. There are hundreds of people who shared all this work with me. Therefore, let me be modest. I'm not the one who made it all happen. We enjoyed the benefit of working with 100 colleagues, about 10 colleagues in my institution, and about 100 colleagues in all the 80s, and so that is the whole story.

PH: Wonderful! It’s always nice to be corrected by you. So thank you. Let us go down memory lane and look at your early days. I have read that you loved tinkering with electronics as a school student. Can you take us back and tell us about the kind of times and what was it like in Chennai back then as a school student and doing these things?

Dr. Ramani: Yes, that’s great for me personally. But it also gives you a glimpse of the times then. I passed out of SSE in 1954. By the time I got involved with Electronics, it was probably 1951 and I was in the 8th or 9th standard. There was a friend of mine called Mahadevan. He and I had a fascination for Electronics. Mahadevan introduced me to the World Book shops where we could buy magazines for ₹8. I could buy a copy of the scientific magazine Popular Science. We used to buy Popular Science issues and learn how to build a crystal radio and go to the boat market and buy a pair of headphones for ₹5 – Second World War surplus phones, crystals and all that. I think I bought the crystal diodes, Germanium and crystals. So, for five or six rupees we would build ourselves a radio. And then we got ambitious and set up a radio. Our radio would receive very weak signals, so we could only listen to Radio Ceylon. Then in those days for ₹6 we bought an NIC valve and built a radio. It was great fun.

PH: Did you always think that you would get into Electronics Engineering? Or that you would get into software? In those days, nobody could even imagine software or computers. So what was your thought process like when you were getting into engineering?

Dr. Ramani: I think I was fortunate enough to recognize that life is very uncertain. What you want to do in life and what you end up doing, are quite different. Therefore, I decided very early that I could not afford to freeze myself into one thought. Like for instance, when I went to the engineering college, they told me that I could not do Electronics because it was not available in the college. Electronics was available only in Chennai. I was studying in Coimbatore, so my college told me that I had to do electrical engineering. That I would never be without a job if I did. The electricity board would always have a job for me and if I wanted, I could study Electronics for my post-graduation.

In those days, my sister was told that girls were not eligible for studying science. There was a woman's college. The seats there had to be filled up first, so she had to study there – any subject that she could. She did exactly that – she studied Home Science. She later got to enjoy the subject and became a professor of Nutrition. But the fact that your college was telling you that you could not study what you liked? Particularly because you were a woman and had to study in a women’s college! It was shocking! However, the new education
policy talks about freedom for the student and that is a big and welcome change.

What I realized while studying, was that I enjoyed learning about technology, particularly the cutting edge of technology. I was interested in Astronomy, Space Science, inter-planetary travel and all kinds of things like that. Computers were hard and there were no books available. My college library did not have a computer book. My friend, Rajgopal, borrowed one from the British Council Library. The British Council Library had one book on computers and you were not supposed to take it out of town. He brought the book, read it and then lent it to me to read. That is how we got into computers. And as a matter of fact, it is the electrical engineering background that made it easier for me to do the Internet related work. And when I completed my studies, I said I will either work with computers or I will join ISRO and work with space technology or aeronautics. So, I had options of two or three things which I was keen on doing.

I'm mentioning this specially to bring out the fact that one has to be flexible in life. Life deals you cards and it’s not for you to choose what kind of cards are dealt to you; you play with what you get. How you play is what matters. I was prepared to deal with the cards that life was dealing me. For instance, I went to [Bombay] Mumbai because I wanted to do my Masters in Electronics. The Registrar said, 'Sorry, you cannot sit for the test for Electronics because you have done only one paper in Electronics for graduation.' I didn't know what to do. I said, "Please allow me to go to the committee and I will ask them for permission." I went to the committee. The committee said, "But you have done very little electronics," and I said, "Sir, ask me questions in Electronics. If I answer them well, you must give me a chance to study the subject."

The committee actually was an Electrical Engineering Committee, but it consisted of very broad-minded people. Professor Bedford, who was the chairman, said it was okay and wanted to test me in Electronics. He asked me a few questions and I answered them. Then he said OK and he went to the electronics committee. He told them, “This guy doesn't want to study with us. You check him out in Electronics;” This is how I got a chance. You never know what happens in life. The committee of Electronics found me suitable for the department. They gave me admission. Such was life. It is nice to remember those days now.

**PH:** So, if you had not thought of meeting with the committee, you probably wouldn't have done Electronics, right? And there is something about the younger generation that they don't come up and ask questions. They don't go beyond what has been set as the rule book. Is that something that you're seeing more and more?

**Dr. Ramani:** In answer to your first question, it didn't require too much [courage] because I had nothing to lose. You want Electronics and you tell them. Coming to your second question, no, I won't blame the younger generation. The truth is, it is the job of a teacher. The most important thing in education is making learning fun. I don't think anything else is more important than that. I am 81 years old and why am I learning things and teaching myself something? Because the biggest pleasure in life is learning. Learn. Enjoy. That is what matters. Getting an award is not important. What is important is that you look forward to learning something throughout your life that you are able to enjoy. I think it is the job of the teacher to instil this culture in us. I've been fortunate in having great teachers all my life.

**PH:** You are a teacher yourself too, we will come to that a little later. So, you did your Masters in Electronics. How did you land up learning computers in those times?

**Dr. Ramani:** You might give me credit for being a bit bored. In my student years I had a peculiar habit. The
first summer in my engineering college, I did not want to waste my time, so I wanted to take up an internship. In those days nobody talked about internships. I went to Oliver Trent asking voluntarily if could work somewhere, do something, learn something? I went to PSG Industries in Coimbatore and learnt very interesting things. The first week I spent learning painting. I think their primary product was water pumps and I spent one week painting water pumps. In the next holidays, I wanted to work in an army workshop. I managed to get into the Army base workshop in Bangalore. There I learnt driving. Once I went to [Bombay] Mumbai and I went around to the Tata Institute of Fundamental Research which had India's first computer. I went there and asked if I could work there in the summer as an intern. They said I was welcome and I started working there, building an electronic device. And really, the device was useful and it worked and then it went places. So, it was a great pleasure for me to learn about computers.

There was a gentle man called Mr. Connie, who taught me some programming. I learned a little from him. That's how I got into computers and learnt programming. I did my academic project in their lab. I could use as many transistors as I wanted to build devices. They had plenty and were glad I used them. Eventually, TIFR offered me a job.

**PH:** How did you get interested in data communication? Where did that come from?

**Dr. Ramani:** The Popular Science that I was reading, taught me not only how to build radio receivers, it also taught me how to build a radio transmitter. I never built a radio transmitter, but the dream was always to build one and be an amateur radio operator. The whole idea was exciting. Amateur radio was the classical thing that took a technology and some imagination and put them together and gave people strange, exciting experiences. I'm going to tell you about the experience of a friend of mine, older than me and a very well-known electronics entrepreneur in India.

Colonel B. K. Rai one day came to the National Center for Software Technology where we were setting up the Internet. And he came as a member of a committee to review our work. I had set up an arrangement whereby an Indian student in the United States would be available on the Internet to talk on the terminal, doing what we call chat nowadays. So this guy was waiting, sitting up awake at 2 a.m. so that he could talk to the committee member who was going to review our work. I told the Colonel that this guy in New Jersey was going to talk to him and started typing. He saw that and put his hand on my shoulder. He said, "I know how you feel." Then he told me his story.

He had studied at Benaras Hindu University as a student. And he was a radio enthusiast. He had built a radio transmitter. In his dormitory there was no table. The radio transmitter was sitting on the floor next to his bed and he would sit on his bed and talk to other people elsewhere in the world. One day he connected with this guy called Louis and he said, "Louis, your signal strength is much higher. How did that happen? Did you get a new transmitter?" And Louis replied, "No, I have moved to Delhi. I used to be in Colombo." Delhi is much closer to Banaras. So the Colonel said, "You are in Delhi? It will be nice if we can meet sometime." Louis said, "Yes, I'm going to come to Banaras next month and I will drop in. I would like to see you and show you my transmitter. You can build one for yourself." The Colonel said he would wait for that day to come.

Then, suddenly about 10 days before the event of Louis's arrival, all hell broke loose. The Principal's Office summoned him. "What have you been doing? You have a radio transmitter in your room." The Colonel acknowledged that he indeed had one. He was told that a gentleman was waiting for him and he was the commissioner of the city. "Your bedroom is not the right place for the transmitter. Bring it to the Physics lab," he was told. The Colonel slowly came to understand that their visitor was actually Lord Louis Mountbatten.

You know they say that on the Internet, nobody knows you're a dog. You can be anybody, whatever. All are equal. So it was in amateur radio.

That is the kind of excitement that amateur radio gave us. When computers made it possible to talk, you know, in the amateur radio days, there must have been a 100 devices in India. I am particularly talking about the British rule days. Not too many people would have had an amateur radio license. But today on the Internet, all of us are chatting or emailing each other. So it was a very smooth transition from excitement with amateur radio to excitement with telecommunications.

**PH:** How were your early days in TIFR?

**Dr. Ramani:** It was 1963 when I went as a student intern. One year later, I joined as an employee, a research assistant. I had big dreams. The dream was about artificial intelligence. I was mostly interested in questions like: How do you solve problems? I was also very interested in how we learn and so on. I wanted to pursue this field. I found the professor in artificial intelligence, Professor R. Narasimhan. He was RN for all of us. He was India's first student of artificial intelligence. He went to the University of Illinois in the U.S. and came back in 1965 and built India's first digital computer.

Now, one should look at the value system of these peo-
A big discovery was the ARPANET (precursor to Internet) useful with AI. It might be 30 years before I was able to do something but it was moving rather slowly. I was a bit worried. It that time was to lay the foundation from great advances fundamental research in Artificial Intelligence going on at that time – Allan Newell. I was fortunate to work with him. Coincidentally, Allan Newell was interested in problem solving – general problem solving. He looked at questions like: How do people think about problems? How do they solve the problems? He was doing fundamental research in that area.

As an engineer, my job was to do things that are useful to people, right? And I enjoyed learning about intelligence, the mystery of how we think and how we learn. Here I was at a leading Artificial Intelligence lab in the world, at a time when back home there were people who couldn’t even have their daily roti. So, I thought it was time for me to give back to society and decided to work in the field of applying Artificial Intelligence to education.

But there was a problem. The problem was that the fundamental research in Artificial Intelligence going on at that time was to lay the foundation from great advances but it was moving rather slowly. I was a bit worried. It might be 30 years before I was able to do something useful with AI.

A big discovery was the ARPANET (precursor to Internet). In Carnegie Mellon, from the first day, all of us sat at the terminal and typed away on the computer. One of the great applications was to ask somebody for a paper of theirs. You sent an email saying could I have a reprint of your paper and through the ARPA it would come in a single day. So, there was a new form of communication - email. I got to know a lot of researchers around the US from whom I could ask for a copy of their paper.

Being an electrical engineer, I looked at the electrical engineering part of the networking. I could understand it. I could build it. And I thought maybe when I go back [to India], though I will primarily work in the area of Artificial Intelligence, I may also build a computer network.

I was torn between the two subjects. Was it right for me to get excited about two different things? I didn’t know and I didn’t worry. There was nothing like ‘right’ back then. So I was introduced to the passions of my life: computer networks, applications of Artificial Intelligence and education. In general, use of technology in education and most importantly, trying to communicate to students the pleasure of learning and having fun.

**PH:** When you went there and started learning about AI, you had scholars like Allan Newall, Marvin Minsky and others. It was more predicate logic based, whereas today’s AI has more of a statistical approach. Where do you think this is headed?

**Dr. Ramani:** I would like to defend Artificial Intelligence, the AI researchers and what they’re doing today. About 10 years ago, I was visiting a university in India and asked, "Who is the faculty member who works with AI?" And my friend told me, "Nobody. AI is not popular. No student wants to take it. No professor wants to teach it." However, in the last decade or so there have been so many advances in the field like face recognition, speech recognition and so on.

The original students of AI are most excited about the fundamental questions: How do we understand? How do we solve problems? How do we pick up language skills? I will tell you what the progress is in understanding language today, even though I’m very excited about the more fundamental things.

I write three blogs, one of them is in Hindi. It is about school science, technology and Mathematics in Hindi and STEM subjects in Hindi. One bad thing in India is people like you and me do not talk in Hindi or our local languages when we talk on social media, YouTube or any public channels. Not on these subjects. Whereas 85% of Indians read and speak in their mother tongue. How can we then abandon our mother tongue when it comes to STEM subjects?

I could have written in any other language or my own mother tongue which is Tamil. I chose Hindi because that’s the language most widely understood, spoken and read in India. But I do not know Hindi that well. So, I started writing in English and used Google Translate to translate it to Hindi. I then sat with the Hindi text and made corrections. I requested one of my colleagues who used to write my speeches in Hindi while I was in NCST, to check the final Hindi version, to ensure that I had not made mistakes. I read the Hindi text and if I felt that some changes were required, then I made the changes in English and converted it to Hindi. I repeated this until it sounded right to me. Then my colleague stepped in.

Why am I saying this? Because this pushed me into
As an engineer, my job was to do things that are useful to people. And I enjoyed learning about intelligence, the mystery of how we think and how we learn. Here I was at a leading Artificial Intelligence lab in the world, at a time when back home there were people who couldn't even have their daily roti. So, I thought it was time for me to give back to society and decided to work in the field of applying Artificial Intelligence to education.

learning Hindi in a more serious way. I realized that to acquire a good vocabulary in Hindi, I had to read Hindi books. While reading was difficult, technology came to my rescue. If I didn't understand a word, I selected the word on my Kindle and I got the translation. I could copy and paste the translation in Google Translate and got to see what Kindle interpreted the word as and how Google saw the same word. I was now using one technology for the other’s implementation, when all along I was the one who was learning.

And then I used Input Tools to write Hindi. I got to type in Roman letters and it would transcribe that very smoothly into Hindi words. Or I could go to the inscript keyboard and type in Hindi script and so on. Would you call it AI?

If I wanted something and said, “Hey, Siri.” The device assistant in my phone answered. “Can you find a translation?” I asked. Siri came back to say, “I found this on the Web,” and so on. Would you call that Artificial Intelligence? Actually AI has this problem where if you can do something, then it's not Intelligence.

Today, we have done a fair amount of work in AI. The fact that the cellphone can understand my voice, can help me and can use the Internet to get me answers or point out where to search on the Internet - are all advances. But you may say that though there is deeper fundamental advance, where is the theory of problem solving? Don’t worry, we’re making progress. It won’t be very long before we do that among the many revolutions we are enjoying.

PH: Did you ever think that you would get involved in building ARPA kind of networks?

Dr. Ramani: I knew I wanted to work with networks; exactly in what formal way I would be able to contribute, was not clear. So, it was one of the dreams to work with computer networks. There were exciting things happening in the world around us. One of them was the notion of Open Access. Open software and public domain software. And there were some people who have encouraged it a lot, like the Americans. The Americans got a lot out of public domain software. The University of California, particularly, was involved in this activity. They had Berkeley Unix, the public domain version of Unix software. In those days, Operating Systems were very expensive. I remember an Operating System for which we received a quote at the time for $600,000. And we couldn't afford it, but the University of California was playing a different game. They were giving away their Unix software free. This version of Unix had been paid for by the U.S. government and was built by university students. The American law has a very interesting principle. When the U.S. government pays for research and a U.S. university develops it, the work is...
in the public domain. And if you put it in the public domain, it is available very cheap. It is also available under American law to anybody in the world. So we wanted to play with Unix. I asked how much it would cost me to get a copy. It was available for a princely sum of under $10 excluding shipping.

That's how we got ourselves BSD Unix and started running it on our new computer. It had the complete version of ARPANET network. We had the source code (not just the running code), so we could recompile it and run it on our computer. We could make whatever changes we wanted. We got into communication software of the variety that the Internet used, which is TCP IP software at almost zero cost. I was working with Unix and realized that we were already at an advantageous position as we had all this technology under our belt; we had understood, learned and used it. We had India’s biggest computer which was running Unix.

In hindsight, by the time we wrote our proposal in 1983 to the government to build an India network which connects to the world, we already had 10 years of experience with building networks.

**PH:** You designed what can be called the first professional course for software developers way back in 1970s. Can you tell us something about it?

**Dr. Ramani:** Our group which became the National Center for Software Technology, did many things, like starting software education in a big way. We offered a post graduate diploma course, probably the first postgraduate diploma course in computer software.

We didn't care for the background of the candidates. You didn't have to be a 17-year old having passed JEE. You could be a 35-year old statistician. You could come and join our part-time course. We had an amazing variety of students. In our first course, we divided the batch into two, with 60 students each and we asked each group to build an Airline Reservation System. I wanted two Project Managers and I asked the students to volunteer. One person immediately raised his hand. I asked him what experience he had in managing people. He said 4000 people reported to him. I asked him what he does and he said he was the Income Tax commissioner for the city. So, that’s the kind of people who joined the course. There were brilliant people from All India Services, from the Indian Railways and yes, academics too.

**PH:** How did you think of the Education Research Network (ERNet)?

**Dr. Ramani:** In those days we were doing many things. Along with software education, we were also building networks. One thing we realized was that we had everything to build anything we could dream of. For our software course, we built our own network, linking TIFR with Victoria Jubilee Technical Institute where the classes were held. We wanted to use Indian-made computers to build the network. So we ordered computers from ECIL in Hyderabad. We leased a telephone line from the department of Posts and Telegraphs and ran our network over TCP/IP, despite warnings that the link might not support it. Here we were happily running the network and then realized that we can actually build a network linking all educational institutions. As researchers, we knew that research groups loved communication. If you need the best paper written in your field, you could just reach out to the person who wrote it and it would arrive by your inbox the next day. I had seen this happening while at C.M.U. in the U.S. So, we proposed to the government that we wanted to build such a network connecting all educational institutions and that this network would be equally owned by all the participating institutions, just like the model U.S had. Our proposal was accepted and soon the IITs joined and then, leading universities, research groups and social groups joined the network.

**PH:** Let’s step back a bit to your days when you were connecting VJTI and TIFR. How many people were involved in this?

**Dr. Ramani:** Of course, I was there as the person heading the project. There were two other people. One of them was Anant Joshi and the other one was Vinod Kumar. They were handling programming. In addition to programming, they also handled a number of other things, like setting up demos. So we were only three and we were building a network between [Bombay] Mumbai and Delhi for the Indian Railways. Once, a senior communications person from the Indian Railways came to visit us. He asked us, "How big is your team?" I said, "You know, there is Vinod Kumar and Anant Joshi. We had another person whose name I took and told him that we were a full four-member team. He was aghast, "What are you telling me," he said, "I have 4000 people reporting to me." Then he said, "I spend one-third of my time sitting in disciplinary proceedings." Actually, just a

**Being an electrical engineer, I looked at the electrical engineering part of the networking. I could understand it. I could build it. And I thought maybe when I go back [to India], though I will primarily work in the area of Artificial Intelligence, I may also build a computer network.**
few dedicated people can build powerful networks.

PH: When you started the ERNet, how much of hand-holding did you have to do with participating institutions? Did you have to prepare computers, load software and send them?

Dr. Ramani: Most of the researchers at the eight participating labs did their own work. We just had to take care of the central equipment. They did research and published a lot of data and all of us went through a fair amount of education due to that. Initially, IIT Delhi and Indian Institute of Science developed terrific capability and others joined forces. So it was a distributed network right from day one.

PH: Around the same time, you proposed that Low Earth orbit satellite communication should be leveraged for data communication. How did that come about?

Dr. Ramani: It’s a very interesting story. Particularly for communication engineers who are interested in history. The fiber optics revolution had not completely had its effect by 1980. It did not have the kind of impact that it did later. At that time, satellite communication was attractive to places where fiber optics could not be made available. Many of us thought of satellite communication as a very important thing for developing countries.

Though fibre optics in recent years has become more easily available and less expensive, and satellite communication lost a little ground, the latter has not completely lost its relevance. Even today, satellite communication has a lot of significance in many respects. We read in the newspaper about villages and children climbing hills in order to access mobile networks. Satellite communication could be of great value even now in places where good infrastructure is not available. This was the situation more or less everywhere in India in 1980s when I was visualizing the applications of satellite communication.

I visualized that within 5-10 years we would have a method of getting communication through your cell phone fairly easily in places where infrastructure was poor. Straight from satellite downloads. What was applicable to India at that time would also be applicable to developing countries in general.

Then there was another angle which was centralized control. A traditional network was controlled by, for instance, a big company. That would cost a fair amount of money for a developing country. So people were working on solving this problem. They wanted to connect remote healthcare centers or remote schools. They wanted to see if there were any modern technologies like the HAM Radio that they could use. Since I was working on similar problems in India, I thought satellite communication was a great answer to their problems.

There was a conference by IDRC (International Development Research Centre), a government funded organization, in Canada. The Canadian parliament had given them grants and they were concerned by the definition. IDRC was concerned about developing countries. Communication was becoming an important idea to worry about, especially developing country communication. They called an international conference and I attended it – it was a workshop. It appeared to me that they were talking about communication problems in many developing countries around the world. They were willing to spend some of their money to solve these problems and they were looking for a solution. I had fresh experience in building 3 city satellite-based networks in India. With that background, I talked about it more and more in the two or three days of the workshop. I came up with the idea that a special kind of satellite for electronic mail and related things would solve the problem. I talked about this with an American scientist, Dr. Robert Miller. I started talking to Dr. Miller and we agreed to work together on this and develop the idea further. We presented a draft paper to IDRC’s communications group and they liked it. They said, “We’re willing to put in some money. Why don’t you develop the paper and publish it at a major international conference?” We agreed and wrote a paper for the annual conference of the International Council for Computer Communication in London, six weeks later.

A lot of people got interested, but the idea remained small. For instance, the amateur radio people got quite excited because they used amateur radio equipment to communicate with the satellite and were also interested in building satellites. So, they said they would go ahead and build it. There was some excitement about this.

PH: Do you still hold out hope that satellite communication as you envisaged it, will make it commercially and improve connectivity?

Dr. Ramani: The technology has to advance to the extent that your cell phone will be able to adapt to satellite communication. And that is not far away. There are small companies around the world working on that, so we do expect yet another wave of interest.

There have been satellite phones, but typically such forms of communication are tightly controlled, because it could be a problem in the hands of a terrorist. As a result, people don’t like to encourage too many satellite-based phones.

Direct satellite-based forms are not commercially viable. However, the truth is, we can work in technology in such a way that the phone you carry in your pock-
There is a revolution every 10 years. Sometimes even faster. I always go with the flow of the revolution. Should I improve electric cars? Should I better automatically piloted vehicles, automatically driven vehicles? Or should I spend money on Artificial Intelligence? I would like to have the freedom to decide what I research on next. Whatever is promising at the time, I will pick it up and hope that I have the guts to be multidisciplinary been informally giving connections. Mr. Vittal said, "Don’t worry about this. Give the Indian software industry email accounts. We have no problem with that. If anybody bothers you tomorrow, I will go to the cabinet committee and tell them that the Indian software industry cannot operate without this technology." This gave us enormous strength.

Later, Mr. Vittal became the Chairman of the Telecom Commission and he did some amazing things. He said he would set up a company called Software Technology Parks of India which would have to buy special equipment such as satellite equipment and had international connectivity. They would give connectivity to our software industry. The STPI would work in multiple cities.

**PH:** You were primarily concerned with building infrastructure. Can you tell us more about your experience of building networks in India?

**Dr. Ramani:** We knew how India needed tens of thousands of software engineers and many of them had to understand losing networks, so we put a lot of energy and effort in their education. We trained people from various industries and with different backgrounds. Soon, I was getting invited by banks to tell them how they could set up a network. And they also started asking us to be consultants. We told them it was important. We were not going to be individual consultants. We were going to be consultants on behalf of NCST.

For instance, The Reserve Bank of India had two committees - one of which was the Rangarajan committee. They were responsible for the computer revolution that came into the banking industry. Similarly, the oil industry told us that they wanted to set up their own networks.
network. So, we acted as consultants to the oil industry. Taking out the technology to the industry, making the industry aware of the possibilities, giving them a helping hand and training their managers - these were things we were doing in addition to our mainstream education.

**PH:** You did a fair amount of work with CMC and its founder Prem Prakash Gupta. P.P. Gupta was a passionate technocrat and his exploits are legendary in India's computerization journey. How was it working with P.P. Gupta and CMC?

**Dr. Ramani:** P.P. Gupta had a Ph.D. from London - I think it was the Imperial College of Technology. He came to India as a country manager for CDC. We got to know him fairly early and he was a half-academic because of his Ph.D. degree. He was very development oriented and his philosophy itself was pretty different. On one occasion, he told me something I will never forget. We were talking about computers and what they could do in India. He said, "Look, we might have computer on some of the floors of the Air India building or some oil company printing salary sheets. I have no objection to that, but that is not my dream. My dream is different. Last Sunday I had gone to the railway station VT. My sister wanted to go to Hyderabad. I had to stand for three hours to buy a ticket. And I don't want that to happen. Why can't we have railway tickets issued by the system so that people can quickly get their ticket while at work?" It was such a beautiful idea. He said, "The goal of computerization in India must change the quality of life and it must serve the common man." P.P. Gupta had this kind of a philosophy. It was very easy to work for him.

Eventually, we built the Passenger Reservation System for the Indian Railways. Then Union minister, Madhav Rao Scindia, championed the cause. Though he promised that it would be ready in a few months, we had to struggle to finish it on time. During his time, P.P. Gupta turned Computer Maintenance Corporation into a software development company.

P.P. Gupta went on to become the Secretary to the Government of India. It was a revolution that the Electronics Department was created. He was first appointed as the chairman of the Electronics Commission. There he put in a lot of effort and achieved a lot. This was in 1980-84. It's so amazing how people come together, you know, people with different philosophies.

**PH:** From the public sector, you joined the private sector. What was your experience like? Why did you join HP labs?

**Dr. Ramani:** The real reason why I left the NCST team was that I felt I would have greater freedom to pursue research in a private lab. There were other pressures, but I did enjoy my time in HP Labs as much as I enjoyed my time in the public sector.

**PH:** If you want to set up a lab now, what kind of a lab would you set up and what problems would you solve?

**Dr. Ramani:** Combining education and research is always great. The lab should ideally have a strong connection with the University because the best research worker is very often a graduate student. The credit goes to the graduate student for an invention. It is not just the salary that you give the graduate student, but the whole credit. It is his thesis. You give him the importance and you make him your equal. So, the incentives in university research are very strong.

**PH:** And what kind of problems fascinate you now?

**Dr. Ramani:** That is a very important question. When I was telling you about the technologies that I was interested in as a graduate student, and the kind of thinking that went on in my mind, I forgot to mention one - atomic energy. My virtual training was in Physics, I came to study engineering after a degree in Physics. So, this was natural. Physics is close to my heart. At that time, I had already done a fair amount of work on my own in nuclear technology. Therefore one of my three areas of work was Electronics and computers. OK, but you see how things change in the world.

To answer your question about what interests me today...that depends. There is a revolution every 10 years. Sometimes even faster. I always go with the flow of the revolution. Should I improve electric cars? Should I better automatically piloted vehicles, automatically driven vehicles? Or should I spend money on Artificial Intelligence? I would like to have the freedom to decide what I research on next. Whatever is promising at the time, I will pick it up and hope that I have the guts to be multidisciplinary.

**PH:** Wonderful. Thank you so much for sharing your story with us.

**Dr. Ramani:** Thank you! You know, I enjoy talking about technology and its possibilities. It inspires me even today.
EXPERIENTIAL LEARNING OF NETWORKING TECHNOLOGIES

Understanding IP Routing

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In the previous article [1], we have studied assignment of IP address [2] to a host, and its role in connecting to internet and communicating with other devices. We explored concept of a network number which is determined using IP address and subnet mask. When network number of two hosts is same, then these two hosts belong to same network else these hosts belong to different networks. Hosts within the same network communicate directly with each other whereas hosts belonging to different network communicate using one or more intermediate routers. A router connects two networks, and its main job is to receive packets from one network and forward it to another network so as to enable the packet delivery towards its final destination. When two hosts are connected by many intermediate networks, communication between these two hosts requires that each of the intermediate routers in the path forward the packet on to the network which is closer to the destination and router in the last leg of this path will deliver the packet to destination host. In this article, we will explore this concept of packet forwarding and the mechanisms used to achieve this packet forwarding.

Consider the connectivity of two networks, say Network-1 and Network-2, as shown in Figure 1. Each of these two networks consists of many connected systems (though as a representation only 2 are shown). Hosts H₁ and H₂ are part of Network-1, and hosts H₃ and H₄ are part of Network-2. These two networks are connected via many intermediate routers, which we can consider as representing the internet. Hosts H₁ and H₂ belong to same network 10.x.x.0/24, and hence can communicate directly without requiring any intermediate router. Similarly, host H₃ communicates directly with H₄ as both belong to same network 10.y.y.0/24. However, when H₁ needs to communicate with H₃, the packets have to go through all the intermediate routers. When H₁ wants to send a packet to H₃, it will forward the packet to router R₁, which in turn will forward the packet to next router R₂, and so on, and finally Router Rₙ will deliver the packet to host H₃. Thus, communication between two hosts involves routing of packets and primary focus of this article is to explore the mechanism used in forwarding these packets.

Whenever, a host needs to send a packet to other hosts, it must know the IP address of destination host. For example, when we use browser to search at google.com, the machine where browser is running, finds the IP address of google.com and then sets up TCP connection using IP address of google.com. When sending a packet, a host consults its routing table (also called as forwarding table) and determine the next hop in the path to destination host. Entries in the routing table play a crucial role in how a host makes a packet forwarding decision. The routing decision using the routing table is always required irrespective of whether the destination host is in the same network or a different network.

1 Routing Table Structure

The main purpose of routing table is to help a host in determining the next hop where packet should be forwarded. The next hop could even be the next intermediate router or the final destination host itself. At its core, routing table has following four column fields, though in many implementations it may have some more information fields, such as cost metric etc., which we will not consider for our discussion.

i. Destination Network.

ii. Subnet mask (for destination network).

iii. Network interface.

iv. Next hop or gateway router's IP address.

A routing table would have number of row entries, with each row corresponding to a destination network. First two fields together identify a network, and are used to check if destination IP address of packet belongs to this network. If this entry matches, then packet is forwarded on the associated interface (3rd field) to the next hop (4th field) of next router.
Next hop entry field is applicable when destination host is not connected to local network and identifies the IP address of next router in the forward path. A typical set of entries for router R₁ in Figure 1 is given below in Table 1, and routing entries for host H₁ is given in Table 2.

**Table 1: Routing entries for R₁**

<table>
<thead>
<tr>
<th>S.N</th>
<th>Destination Network</th>
<th>Netmask</th>
<th>Interface</th>
<th>Next Hop</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.x.x.0</td>
<td>/24</td>
<td>e₁</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>a.b.c.d</td>
<td>/n₁</td>
<td>e₂</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>4</td>
<td>p.q.r.s</td>
<td>/n₁₋₁</td>
<td>e₂</td>
<td>IP address of R₂</td>
</tr>
<tr>
<td>5</td>
<td>10.y.y.0</td>
<td>/24</td>
<td>e₂</td>
<td>IP address of R₂</td>
</tr>
<tr>
<td>6</td>
<td>0.0.0.0</td>
<td>/0</td>
<td>e₂</td>
<td>IP address of R₂</td>
</tr>
</tbody>
</table>

**Table 2: Routing entries for Host H₁**

<table>
<thead>
<tr>
<th>S.N</th>
<th>Destination Network</th>
<th>Netmask</th>
<th>Interface</th>
<th>Next Hop</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.x.x.0</td>
<td>/24</td>
<td>Ethernet</td>
<td>10.x.x.1</td>
</tr>
<tr>
<td>2</td>
<td>0.0.0.0</td>
<td>/0</td>
<td>Ethernet</td>
<td>10.x.x.1</td>
</tr>
</tbody>
</table>

First two entries in Table 1 correspond to two networks to which router R₁ is directly connected and hence there is no next hop address. These will be followed by number of entries corresponding to network numbers that exist in the network. The entries in 4th and 5th rows correspond to two networks connected with the router R₂. Lastly, there is an entry corresponding to 0.0.0.0/0 which is also referred to as default route entry. Use of this default entry is explained ahead. For any host which is typically connected to a single network, there are generally two entries, as shown in Table 2 for host H₁. One entry corresponds to local network and other entry corresponds to default network i.e. 0.0.0.0/0. These entries are sorted in the decreasing order of number of bits in netmask. For example, entry for netmask /27 will come before entries of netmask /26 or /25 etc.

2 Using Routing Table to Forward Packets

When a host needs to send a packet to destination host or an intermediate router needs to forward a received packet, then both the host and the router use a routing algorithm to determine how to send the packet to next hop or directly reachable destination host. An outline of such a routing algorithm is given in Table 3.

**Table 3: Routing Algorithm**

01: #Algorithm For forwarding the packet
02: Extract the destination address from the packet
03: Repeat the following for each entry in routing table
04: Apply the netmask (2nd field) and compute network number
05: Compare it with destination network (1st field)
06: If matche
07: Forward packet to next-hop on listed interface (3rd field)
08: Exit // routing is over
09: Else
10: Continue to next entry
11: When no match found (entry 0.0.0.0/0 not defined)
12: Drop the packet
13: Inform the sender (ICMP error message)

Consider the network given in Figure 1, and that host H₁ (belonging to Network-1) needs to send a packet to host H₃ (belonging to Network-3). Thus the source and destination addresses of this packet would correspond to 10.x.x.11 and 10.y.y.131. Routing algorithm makes use of only the destination address and does not consider the
source address, and works as follows. Routing table of host H₁ (Table 2) has just two entries. Using the destination address 10.y.y.131 (as extracted from the IP packet in line 02 of Table 3), the lines 03 to 10 of routing algorithm will be applied to this destination address. Applying the netmask /24 of first entry in the routing table (Table 2) to destination address 10.y.y.131 (line 04), network number is computed as 10.y.y.0. For a detailed discussion on computation of network number, reader can review the article by as given in [1]. Comparison (line 05) of computed network number with destination network 10.x.x.0 for first entry fails and hence routing process repeats as per line 09–10 for the next entry. For the 2nd entry (Table 2), netmask is /0, and applying this netmask to 10.y.y.131 gives the network number as 0.0.0.0. This computed network number matches with destination network in 2nd entry of routing table of H₁, and thus packet is forwarded to router R₁ on Ethernet interface of host H₁. Applying netmask /0 with any IP address will always compute the network number as 0.0.0.0 and thus it will always match the destination network and therefore this is called the default route entry i.e. when no other routing entry matches, this entry will always match. The default route entry in a routing table always appears as the last entry.

3 Delivering Packet to Next Hop and ARP Protocol

When host H₁ is sending the packet to host H₃, it only contains source IP address (H₁) and destination IP address (H₃). The packet does not have IP address of either router R₀ or any of the intermediate router(s). So, it is important to understand the mechanism used in delivering this packet to router R₁ (next hop address). Any system is connected to a network via its link layer adaptor e.g. ethernet interface. Each link layer adaptor has its link layer address, also known as MAC (Medium Access Control) address for ethernet adaptors. MAC address is a popular term and thus in general, any link layer address is called as MAC address. The MAC address consists of 6 bytes and generally written in hexadecimal notation. Windows systems use dash as separator of two bytes, and therefore, MAC address in a windows system will be shown as xx-xx-xx-xx-xx-xx. In Linux, colon(:) is used as the separator and thus MAC address is shown as xxxx:xxxx:xxxx. An interesting property of MAC address is that it is unique across the world i.e. no two adaptors can have same MAC address. The MAC address is assigned by link adaptor manufacturer and entire MAC address space is managed by IEEE (Institute of Electrical and Electronic Engineers). Thus, whenever anyone wants to manufacture the link layer adaptors, they need to get a block of addresses (corresponding to first 3 bytes of MAC address) from IEEE and assign the remaining 3 bytes uniquely to each of the adaptors that company will manufacture. Thus, MAC address is not configurable by a user and is fixed with the adaptor whereas IP address is user configurable and assigned by a network administrator.

Whenever a machine sends a packet, the packet goes out from the link layer adaptor, which inserts its MAC address as the source MAC address in the transmitted frame. The sender also needs to correctly fill the destination MAC address field in the transmitted frame, which is required for receiving host to receive and process it. When link layer adaptor of receiving host receives a frame, it compares the received destination MAC address in the frame with its own MAC address. Only when two addresses match, the adaptor receives the frame, extracts the network layer packet and passes it on to host for further processing by upper layer network stack. If the MAC address match fails, then adaptor simply discards the frame and network layer will not even see this packet. A link layer adaptor also receives and processes all those frames which have destination MAC address set as broadcast MAC address (all bits in the MAC address field are set to 1) and written as FF:FF:FF:FF:FF:FF.

Thus, for host H₁ to forward the packet to router R₁ (Figure 1), it must fill the MAC address of the network interface e₁ of router in the transmitted frame. From the routing table, it only knows the IP address of router R₁. The MAC address of R₁ (e₁) interface, let say it is MACᵣᵣₑ₁, is known only to R₁. Unless the sender host fills this MAC address in the frame being sent, R₁ will never receive this packet. Thus, we need a protocol that enables a sender host to obtain the MAC address corresponding to IP address of receiver host. This functionality is provided by address Resolution Protocol (ARP) [3]. ARP protocol enables the sender host to find out the MAC address of next hop (immediate recipient of packet) given its IP address. The protocol works as follows. Sender host broadcasts an ARP Request message to all machines in the local network by setting the destination MAC address as broadcast address i.e. FF:FF:FF:FF:FF:FF. This ARP request message is received by all the machines in the local network as its destination MAC address is broadcast address. Link layer adaptor of each host receives this frame, extracts the network packet from it, and passes this request message to ARP module (network layer) for further processing. ARP module of each host compares the IP address in the received ARP Request message with its own IP address. If the match fails, then ARP module simply discards the message. This match will fail for all systems except one (whose IP address matches). For example, H₁ will send ARP Request asking for MAC address corresponding to IP address 10.x.x.1 (e₁ interface of R₁). The ARP module of router will find the match successful since ARP Request is for its own IP address and all other hosts in Network-₁ will discard this ARP request.
The router $R_1$ then responds with ARP Reply message providing MAC address of its $R_1(e_1)$ interface. $R_1$ already knows the MAC address of $H_1$ since this was the source MAC address when ARP request message was received and thus it does not need to make another ARP Request. When $H_1$ receives the ARP Reply, it makes a note of the MAC address of $R_1(e_1)$ and stores it in its ARP table.

Now for the original data packet that $H_1$ wants to send to $H_3$, the link layer frame sent by $H_1$ will have source MAC of $H_1$ and destination MAC corresponding to $R_1(e_1)$ interface, source IP as 10.x.x.11 ($H_1$) and destination IP as 10.y.y.131 ($H_3$). When this packet is transmitted by $H_1$, link layer adaptor of $R_1$ will receive this frame and pass it to higher layer of router which will process it further. The router $R_1$ will apply its routing algorithm (Table 3) to determine the next hop. Routing algorithm will evaluate entries from the routing table (Table 1) one at a time till it finds a match for the destination IP of 10.y.y.131. The first entry will compute network number as 10.y.y.0 which does not match destination network (1st field) 10.x.x.0 and thus routing algorithm evaluates 2nd entry. Again, this will not match and process goes on for remaining entries. The match will occur for 5th entry where computed computer number is 10.y.y.0 as well as destination network (1st field) for 5th entry is also same. Thus, router will forward the packet to next hop router (4th field) $R_2$. Routing algorithm only provides the IP address of next hop router and not the MAC address. Router $R_1$ will follow the same process as described earlier to find the MAC address of $R_2$’s network interface. $R_1$ will send ARP request for $R_2$, $R_2$ will respond with ARP Reply and then $R_1$ will forward the packet with source IP as 10.x.x.11 and destination IP as 10.y.y.131 to $R_2$. This link layer frame will have source MAC corresponding $R_1(e_1)$, and destination MAC corresponding to $R_2$ (network interface). When $R_2$ receives this packet, it will follow the same process of finding the MAC address of next hop router, forward the data packet with source IP as 10.x.x.11 and destination IP as 10.y.y.132 and forward it to next hop router. This process will be followed at each intermediate router till last router $R_n$ receives this packet and delivers this packet to $H_3$. Thus, in each hop, source IP and destination IP remains the same, but source MAC and destination MAC will change on per hop (link layer connectivity) basis.

The set of steps for experiential exercise to understand the packet delivery within the same network is given in Exercise 1.

4 Constructing Routing Table

Internet consists of many networks which are connected by a number of routers. A router needs to build its routing table so as to be able to forward the packet correctly in the right direction towards the destination. Building of routing table can be done either manually (e.g. network admin configuring the routing table of each involved router) or dynamically by routers themselves. When number of networks are large, it is infeasible to build the routing table manually. However, to understand its construction and get an experiential exposure, we will first explore the process of building a routing table manually and later on briefly dwell upon building these dynamically. To build these tables manually, consider a simple network consisting of three hosts $H_1$, $H_2$ and $H_3$ (as shown in Figure 2), where each host is associated with multiple networks. This simple network setup is sufficient to lay the foundation of routing table construction.

![Multi network connectivity using VMs](image)

**Figure 2:** Multi network connectivity using VMs

From implementation perspective of this network, a typical reader of this article would have access to a single laptop, and thus we will make use of virtual machines to setup such a network. This requires installing some virtualization software, such as VirtualBox[7], VMWare[9], Parallels[8] (only for Mac) etc., on the host system (i.e. laptop running Windows, or Macbook etc.). The above depicted network is created using 2 Virtual Machines running Ubuntu$^1$ 16.4LTS ($H_1$) and 18.4LTS ($H_2$) along with the host OS ($H_3$). Author of this article is using Macbook (host $H_3$) as the host OS and has created the Ubuntu VMs using Parallels[8] virtualization software. The network 10.211.55.0/24 is created by virtualization software and all VMs attach to this network. Two Ubuntu VMs

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$^1$Any other version of Ubuntu would work equally well.
(H₁ and H₂) get their respective network addresses as 10.211.55.10/24 and 10.211.55.11/24 and host system is assigned the IP address 10.211.55.2/24. As all 3 systems belong to same network, these can communicate with each other directly without requiring any connecting router.

**Table 4:** Assigning Multiple IP addresses to host H₁

```
# Assigning addresses to host H₁
# Addresses on power up of H₁
01: H₁ > ip -4 addr show
1: lo: <LOOPBACK,UP,LOWER_UP> mtu 65536 ... inet 127.0.0.1/8 scope host lo ...
2: enp0s5: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1500 ...
    inet 10.211.55.10/24 brd 10.211.55.255 scope global dynamic enp0s5 ...

# Assigning new network addresses to enp0s5 and lo interface of H₁
02: H₁ > sudo ip addr add 10.1.2.1/24 dev lo
03: H₁ > sudo ip addr add 10.1.3.1/24 dev enp0s5
```

**Table 5:** Assigning Multiple IP addresses to Host H₂

```
# Assigning addresses to host H₁
# Addresses on power up of H₁
01: H₂ > ip -4 addr show
1: lo: <LOOPBACK,UP,LOWER_UP> mtu 65536 ... inet 127.0.0.1/8 scope host lo ...
2: enp0s5: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1500 ...
    inet 10.211.55.11/24 brd 10.211.55.255 scope global dynamic enp0s5 ...

# Assigning new addresses to enp0s5 and lo interface of H₂
02: H₂ > sudo ip addr add 10.1.4.1/24 dev lo
03: H₂ > sudo ip addr add 10.1.5.1/24 dev enp0s5
```

Understanding of routing and building a routing table requires us to work with more than one network. Though at the time of VM invocation, they belong to only one network, we will create 4 more networks, and assign two networks to each of Ubuntu VM using its ethernet interface en0s5 as well as loopback lo interface. We will make use of the phenomenon of assigning a number of network addresses (even belonging to different networks) to a network interface. Table 4 and Table 5 respectively provide Linux commands to assign multiple IP addresses to interfaces of hosts H₁ and H₂. Line 01 (Table 4) shows the existing IP addresses belong to loopback and ethernet interfaces of host H₁. Lines 02 and 03 assign the new network addresses respectively to loopback and ethernet interfaces. These new addresses are in addition to existing addresses and same is shown in output of command at line 04. Similarly, lines 01-04 (Table 5) shows the assignment of new network addresses to host H₂. The
hands on
ethernet interface name would vary depending upon VM Ubuntu installation, and thus reader should appropriately replace it in the network setup being created for experiential learning as described in experiential exercises.

With the creation of 4 new networks, host H₁ does not know the route to reach the network 10.1.4.0/24 and 10.1.5.0/24. Similarly, host H₂ does not know how to reach the networks 10.1.2.0/24 and 10.1.3.0/24. Reachability to these networks requires creation of routing entries in the routing tables of H₁ and H₂ respectively. Host H₁ (IP address 10.211.55.10) can reach both 10.211.55.11(H₂) and 10.211.55.2(H₃) as all three addresses belong to same network with network number 10.211.55.0/24. Similarly, host H₂ (10.211.55.11) can reach both 10.211.55.10(H₁) and 10.211.55.2(H₃). The networks 10.1.4.0/24 and 10.1.5.0/24 are reachable via 10.211.55.11(H₂) and thus H₂ can act as gateway for these two networks. Similarly, networks 10.1.2.0/24 and 10.1.3.0/24 are reachable via 10.211.55.10(H₁), and thus H₁ can act as gateway for these two networks.

Using this reachability knowledge of these new networks, routing table entries for these networks on H₁ and H₂ are created using each other as the gateway. The commands to create the routing entries are shown in Table 6. The command “ip route add” (lines 02-03) has basically four parameters corresponding to four fields of the routing table (Table 1). As H₁ and H₂ are hosts (end systems) and are connected to multiple networks, these systems are known as multi-homed hosts, as a host either consumes (receives) or generates (sends) a packet. To enable routing functionality in a host so that it can forward packets across the connected networks, it needs to be configured as a router i.e. forward packets across interfaces/networks. The commands in Table 6 at line 01 and 05 enable routing functionality in these two hosts. Line 02 (Table 6) adds the routing entry for network 10.1.4.0/24, next hop gateway as 10.211.55.11 (H₂) and packet has to be sent out on interface enp0s5. Similarly, command at line 03 adds the routing entry in H₁ for 2nd network 10.1.5.0/24. Similarly, lines 06–07 demonstrate creation of routing entries in host H₂.

Table 6: Creating Routing table

<table>
<thead>
<tr>
<th># Creating routing table at H₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>01: H₁&gt; sysctl -w net.ipv4.ip_forward=1</td>
</tr>
<tr>
<td>02: H₁&gt; sudo ip route add 10.1.4.0/24 via 10.211.55.11 dev enp0s5</td>
</tr>
<tr>
<td>03: H₁&gt; sudo ip route add 10.1.5.0/24 via 10.211.55.11 dev enp0s5</td>
</tr>
<tr>
<td>04: H₁&gt; ip -4 route show</td>
</tr>
<tr>
<td>default via 10.211.55.1 dev enp0s5 proto static metric 100</td>
</tr>
<tr>
<td>10.1.3.0/24 via 10.211.55.11 dev enp0s5</td>
</tr>
<tr>
<td>10.1.4.0/24 via 10.211.55.11 dev enp0s5</td>
</tr>
<tr>
<td>10.1.5.0/24 via 10.211.55.11 dev enp0s5</td>
</tr>
<tr>
<td>10.211.55.0/24 via enp0s5 dev enp0s5 proto kernel scope link src 10.211.55.10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th># Creating routing table at H₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>05: H₂&gt; sysctl -w net.ipv4.ip_forward=1</td>
</tr>
<tr>
<td>06: H₂&gt; sudo ip route add 10.1.2.0/24 via 10.211.55.10 dev enp0s5</td>
</tr>
<tr>
<td>07: H₂&gt; sudo ip route add 10.1.3.0/24 via 10.211.55.10 dev enp0s5</td>
</tr>
<tr>
<td>08: H₂&gt; ip -4 route show</td>
</tr>
<tr>
<td>default via 10.211.55.1 dev enp0s5 proto dhcp metric 100</td>
</tr>
<tr>
<td>10.1.2.0/24 via 10.211.55.10 dev enp0s5</td>
</tr>
<tr>
<td>10.1.3.0/24 via 10.211.55.10 dev enp0s5</td>
</tr>
<tr>
<td>10.1.5.0/24 via enp0s5 dev enp0s5 proto kernel scope link src 10.211.55.10</td>
</tr>
<tr>
<td>10.211.55.0/24 via enp0s5 dev enp0s5 proto kernel scope link src 10.211.55.10</td>
</tr>
</tbody>
</table>

The routing table entries are shown as output of line 04 (host H₁) and 08 (host H₂). Routing entries for H₁ shows that network 10.1.3.0/24 is directly connected using enp0s5 (network interface) and there is no (via) gateway. For networks 10.1.4.0/24 and 10.1.5.0/24, the next hop gateway is 10.211.55.11 (i.e. H₂) reachable via network interface enp0s5. Similarly, line 08 shows the routing entries for host H₂. Now if from H₁, when “ping -c2 10.1.4.1” or “ping -c2 10.1.5.1” is invoked, two ICMP requests will be sent to these addresses via host H₂ and corresponding responses will be received. A successful ping response implies that routing table entries are correct. Ping to any other unassigned network IP address e.g. 10.1.5.2 will result in timeout and no response will be received. It is interesting to know that when an IP address is assigned to a loopback interface in Linux, it automatically assumes that all IP addresses belong to it as well. Thus, when IP address 10.1.4.2 or 10.1.4.200 is pinged from H₁, it will still be successful even though these IP addresses are not directly assigned to loopback interface of H₂ and neither shown (line 04 Table 5).
The set of steps for experiential exercise to construct the routing table and its usage in delivering packet to next hop router is given in Exercise 2.

5 Route Aggregation

Internet consists of large number of networks and if a router needs to keep an entry for each network, then number of entries in routing table are likely to exceed millions and thus puts a constraint on memory and compute resources of a router. Routers would like to minimize the number of routing entries and thereby improve upon the packet forwarding performance. The technique to minimize the number of routing entries is achieved by using route aggregation mechanism, in which multiple routing entries are aggregated into a single routing entry. To understand route aggregation mechanism, consider simple network setup as shown in Figure 2. Host H1 acts as the gateway for 2 networks 10.1.4.0/24 and 10.1.5.0/24 and correspondingly there are 2 routing entries in the routing table of H1. For the routing purpose from the perspective of H1, both the networks 10.1.4.0/24 and 10.1.5.0/24 are reachable via gateway H2. Thus, if these two networks can be aggregated into a single network, H1 will have only one routing entry for these two networks. These two networks are contiguous, each having 256 IP addresses, and thus can be aggregated as 10.1.4.0/23 representing a total of 512 IP addresses. Thus, a single routing entry can be created using the command “ip route add 10.4.1.0/23 via 10.211.55.11 dev enp0s5”. This technique of using a single subnet prefix (mask) to aggregate and advertise multiple network is also called route summarization or address aggregation.

Address aggregation requires that networks being aggregated should be contiguous and have same number of IP addresses in them. However, though this is a necessary requirement but not sufficient. For example, two networks 10.1.1.0/24 and 10.1.2.0/24 can’t be combined into a single network with a prefix of /23, though both the networks have 256 IP addresses and are contiguous. The summarized network number and the two (or more) networks being combined must have the same higher order bits in the network portion, and should follow the proper hierarchical fashion of address allocation. In this example, first network 10.1.1.0/24 has high order 23 bits as “00000101 00000000 00000000” and the second network 10.1.2.0/24 has high order 23 bits as “00000100 00000000 00000000”. These high order 23 bits differ in last bit i.e. 23rd bit which is value 0 for first network and value 1 for the second network. However, since these two networks have high order 22 bits as same i.e. “00000100 00000000 00000000”, so one would like to aggregate these as 10.1.0.0/22. This cannot be done since the subnet prefix of /22 will have 10 bits in its host part and thus total number of possible IP addresses in the aggregated network would become 1024. This would imply that this aggregation will include the network 10.1.0.0/24 as well as the network 10.1.3.0/24, which are not part of original aggregation.

So, requirements for route summarization of N networks are listed as below.

1. The number N should be equal to some power k of 2 i.e. N=2k where 0<k<31.
2. All the networks should have same number of IP addresses i.e. they should have same subnet prefix (mask) e.g. /m.
3. The networks should be contiguous i.e. when the range of IP addresses of one network ends, the next IP address starts the range of next network (being aggregated).
4. The high order m-k bits in aggregated network should be same in all individual networks which are being summarized. The subnet prefix of aggregate network would become /m-k i.e. k number of bits will be taken from network part and added to host part. Thus, total number of IP addresses in aggregated network would be equal to 2m-k.

Let us illustrate the summarization process using an example. Consider the following 8 (= 2^3) networks with their representation in bits with network part (highlighted in yellow) and host part (in orange) shown as separated by “|” (and last 3 bits of network parts are underlined and in italics).

i. 172.16.32.0/23 i.e. 10101100 00010000 0010000 | 00000000/23
ii. 172.16.34.0/23 i.e. 10101100 00010000 0010001 | 00000000/23
iii. 172.16.36.0/23 i.e. 10101100 00010000 0010010 | 00000000/23
iv. 172.16.38.0/23 i.e. 10101100 00010000 0010011 | 00000000/23
v. 172.16.40.0/23 i.e. 10101100 00010000 0010100 | 00000000/23
vi. 172.16.42.0/23 i.e. 10101100 00010000 0010101 | 00000000/23
vii. 172.16.44.0/23 i.e. 10101100 00010000 0010110 | 00000000/23
viii. 172.16.46.0/23 i.e. 10101100 00010000 0010111 | 00000000/23
The total number of networks are $2^3 = 8$, have same subnet mask of /23, and are contiguous. High order 20 (=23-3) bits are same in all these 8 networks and thus, subnet prefix of aggregated network would be equal to /20 (=23-3), as 3 bits are moved from network part to host part. The new aggregated network number would become 172.16.32.0/20.

When any of the above-mentioned requirement is not satisfied, then networks can’t be aggregated. For example, consider the middle 4 (= $2^2$) networks, that is, 172.16.36.0/23, 172.16.38.0/23, 172.16.40.0/23, and 172.16.42.0/23. Thus, the subnet prefix of aggregated network should be /21(=23-2). The 21st high order bit value is 0 in first two networks and has value 1 in the last two networks. Since the last requirement is not met, these 4 networks can’t be aggregated. However, if we consider the first 4 networks, that is, 172.16.32.0/23, 172.16.34.0/23, 172.16.36.0/23 and 172.16.38.0/23, these satisfy all the requirements and thus can be aggregated into the network 172.16.32.0/21. Similarly, if we consider the last 4 networks, that is, 172.16.40.0/23, 172.16.42.0/23, 172.16.44.0/23, and 172.16.46.0/23, these meet all the requirements and can be aggregated as 172.16.40.0/21.

The set of steps for experiential exercise to learn route aggregation and use the route summarization to forward packets in real networks is given in Exercise 3.

6 Longest Prefix Match in Routing Table
Route summarization is typically done when all the networks being aggregated are reachable from same router. This is typically done at ISP (Internet Service Provider) routers. However, at times, some customer of an ISP, which initially belonged to an aggregated network, moves out to another ISP and thus no more reachable by aggregated routing, as it is connected by a different ISP router. Then as per aggregation requirements listed earlier, route summarization fails and number of routing entries increases from 1 summarized entry to many entries corresponding to remaining networks. It is imperative for efficiency reasons to minimize the number of entries in the routing table of a router and thus a router would still prefer to use route summarization though excluding the network which has just moved to a different router. This requirement of still using route summarization to minimize number of routing entries even though some network has moved out of aggregation is served by a routing technique known as Longest Prefix Match.

Consider the network as shown in Figure 3. One customer network 172.16.36.0/23 has moved from ISP$_1$ to ISP$_2$. Before this network movement to ISP$_2$, all the 8 networks were reachable via router ISP$_1$. Thus, router R$_0$, had a single aggregated routing entry for these 8 networks as destination network/mask: 172.16.32.0/20, next hop: ISP$_1$, and network interface e$_0$. After this network moves from ISP$_1$ to ISP$_2$, route summarization conditions are violated and thus these can’t be summarized in a single route. So, router R$_0$ needs to either create individual entries for each of the 7 networks in the routing table, or alternatively partially summarize these creating 4 entries as shown in Table 7. Using longest prefix match mechanism, the number of routing entries for these networks can be reduced to 2, one corresponding to aggregated network and one corresponding to the network that has moved out of aggregation as shown in Table 8.

### Table 7: Partial route summarization

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Destination Network</th>
<th>Netmask</th>
<th>Interface</th>
<th>Next Hop</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>172.16.32.0</td>
<td>/22</td>
<td>e$_0$</td>
<td>ISP$_1$</td>
</tr>
<tr>
<td>2</td>
<td>172.16.36.0</td>
<td>/23</td>
<td>e$_1$</td>
<td>ISP$_2$</td>
</tr>
<tr>
<td>3</td>
<td>172.16.38.0</td>
<td>/23</td>
<td>e$_0$</td>
<td>ISP$_1$</td>
</tr>
<tr>
<td>4</td>
<td>172.16.40.0</td>
<td>/21</td>
<td>e$_0$</td>
<td>ISP$_1$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td></td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.0.0.0</td>
<td>/0</td>
<td>e$_2$</td>
<td>IP address of R$_2$</td>
</tr>
</tbody>
</table>
Consider that Router \( R_0 \) gets a packet with destination address of 172.16.36.1. When router \( R_0 \) applies routing algorithm as described in Table 3 to the entries of Table 8, row 1 computes the destination network as 172.16.36.0/23 and row 2 computes the destination network as 172.16.32.0/20. Thus, routing algorithm matches both entries corresponding to row 1 and 2, each identifying different next hop router with different network interface. However, a packet can only be forwarded to one of these two next hops and not both. Approach of longest prefix match resolves the issue of multiple matching, and states that choose the routing entry that has the longest prefix (subnet mask) in the 2nd column of routing table. Thus, in this case, router \( R_0 \) will choose the entry corresponding to prefix /23 rather than /20 since former has longer prefix (23 bits) compared to the latter which has shorter prefix (20 bits). Thus, router \( R_0 \) correctly forwards this packet on interface \( e_1 \) to next hop router \( ISP_2 \). Sequential searching in the routing table to find the entry with longest prefix is optimized by organizing these entries in the routing table starting from longest prefix to shorter prefix. Thus, using routing algorithm, entry with longest prefix will be matched first and packet will be forwarded without even matching with other entries with shorter prefix. However, high end router instead of searching sequentially, use Content Addressable Memories (CAM) technique to search the entries for the given IP address which perform search in \( O(1) \) time rather than \( O(n) \) taken by sequential search, and use longest prefix match to select the next hop.

The set of steps for experiential exercise to create the network setup with longest prefix match routing and corresponding forwarding of the packets is described in Exercise 4.

### 7 Dynamic Routing

So far, we have used static (manual) approach to create routing entries in routing table. This approach works fine when underlying network is of small size, and network topology is fairly static and rarely undergoes any changes. In such networks, any topology change occurs over a longer period of time e.g. few months or even years. For example, a college network generally does not undergo any changes unless a new laboratory or department is created or course contents are modified which occur mostly on yearly basis. Creation of manual entries does not work for a large network, as entries have to be manually created for all the routers in the network. When configuring large number of routers with manual entries, the chance of making a configuration error is quite high and it take humongous efforts to identify and rectify such configuration errors. Further, larger network would undergo changes more frequently, such as, a link going down or coming back up or a router crashing, etc. Any such change in network topology would require updates in routing tables of all routers in the network which is a tedious task, likely to cause more manual errors and thus neither manageable nor scalable.

In larger size networks, routers use routing protocols to create the routing tables automatically. Routers exchange information about connected and reachable networks with other routers, and build their routing table. Any change in network topology e.g. a link going down or coming back up, a new router being added into the network or some working router going down is detected by neighbouring routers of the affected link/router. This topology change results in immediate exchange of routing information by neighbouring routers to other routers and eventually percolated to all routers in the network. Thus, in a short time (known as convergence time), all routers of network get the routing update about the changes in network topology and update their routing table. These routing protocols are classified into two categories [10], a) Link State Routing, and b) Distance Vector Routing. Open Shortest Path First (OSPF)[4] is a link state routing protocol which is widely implemented by many network administrators. Routing Information Protocol (RIP) [5][6] implements distance vector routing approach and was the routing protocol which was first implemented and distributed as part of BSD Unix (Berkeley System Division Unix) distribution. It is practically infeasible to build a real live network to explore dynamic routing protocols using experiential learning as it would involve setting up of fairly sufficient number of systems and routers, to which reader of this article may not have access. Interested readers are requested to explore these by going through references and text books on networks and understand working of dynamic routing protocols.

### 8 Summary

We have discussed need of IP routing to deliver packets from one system to another, when these are connected either directly on the same network or via a number of intermediate routers. Each router as well as a host in the...
network maintains a routing table, and uses routing algorithm to forward packets. A typical routing table needs minimum of 4 entries, namely a) destination network, b) netmask (or prefix), c) network interface, and d) IP address of next hop router. Routing table needs to have one entry for each of the network numbers present in the network setup. Generally, a routing table also has a default entry as 0.0.0.0/0 so that it matches all destinations. We have also explored the need of ARP protocol to map an IP address to MAC address as latter is needed by link layer adaptors to receive and process the frame and pass the extracted network packet to higher layer network stack in the system for further processing. When a packet is forwarded by one intermediate router to next, it does not change source and destination IP address as provided originally by the sender host. The delivery to next hop is achieved by adding the destination MAC address of next hop router by the previous router/host in the path from source to destination. As internet consists of a large number of networks, technique of route summarization (also called as route aggregation) is used to summarize multiple routing entries in a single route to minimize the number of routing entries to improve the routing performance. We have also discussed use of longest prefix match to correctly route the packets when some networks that were part of route aggregation, move to a different router.

9 Experiential Exercises

To understand and learn IP routing experientially, an experimental setup similar to the one shown in Figure 2 is used for hands-on exercises. One can either use 3 independent systems, or using a single system, create two Ubuntu VMs (Virtual Machine) using virtualization software \[7\][\[8\]][\[9\]] to create such a network. The host OS (that runs virtualization application) can be Windows, Macbook or Linux. In the exercises described below, the network number used by VMs is shown as 10.211.55.0/24 and this may vary depending upon the VM network being used. When a packet is forwarded by one intermediate router to next, it does not change source and destination IP address as provided originally by the sender host. The delivery to next hop is achieved by adding the destination MAC address of next hop router by the previous router/host in the path from source to destination. As internet consists of a large number of networks, technique of route summarization (also called as route aggregation) is used to summarize multiple routing entries in a single route to minimize the number of routing entries to improve the routing performance. We have also discussed use of longest prefix match to correctly route the packets when some networks that were part of route aggregation, move to a different router.

To understand the working of IP routing and ARP protocol, run wireshark on both H\(_1\) and H\(_2\) and capture packets for IP addresses of source and destination addresses used for communication.

**Exercise 1**

**Topic: Routing and delivery of packets when two systems are connected directly on a network**

a. Power on H\(_1\) (VM1 - Ubuntu) and login into H\(_1\).

b. Find out the IP addresses of both loopback and ethernet interfaces. The loopback (lo) interface would always have IP address as 127.0.0.1 and ethernet (enp0s5) would have IP address like 10.211.55.10/24 (this IP address may vary depending upon the VM network being used). Use the command below to find the IP addresses (shows in highlighted yellow)

```
H1> ip -4 addr show
```

1: lo: <LOOPBACK,UP,LOWER_UP> mtu 65536 qdisc noqueue state UNKNOWN group default qlen 1
   inet 127.0.0.1/8 scope host lo
      valid_lft forever preferred_lft forever
2: enp0s5: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1500 qdisc pfifo_fast state UP group default qlen 1000
   inet 10.211.55.10/24 brd 10.211.55.255 scope global ephemeral enp0s5
      valid_lft 1718sec preferred_lft 1718sec

c. Analyze the routing table entries. It should basically have two entries. First one for default destination (0.0.0.0/0) with the next hop as gateway (via) address 10.211.55.1 and second one belonging to local (VM) network 10.211.55.0/24 without any next hop (via). Use the command below to find the routing information (destination network is shown in highlighted yellow)

```
H1> ip -4 route show
```

```
default via 10.211.55.1 dev enp0s5 proto static metric 100
10.211.55.0/24 dev enp0s5 proto kernel scope link src 10.211.55.10 metric 100
169.254.0.0/16 dev enp0s5 scope link metric 100
```

d. Analyze the ARP table entries. It should basically have one entry corresponding to default gateway 10.211.55.1. Use the command below to find ARP table entries. The MAC address corresponding to default gateway would vary as per network setup.
Depending upon the network activity it may show more entries as well.

H1> `arp -an`

? (10.211.55.1) at 00:1c:42:00:00:18 [ether] on enp0s5

e. Power on H2 (VM2-Ubuntu) and repeat the steps described above to find the IP address (10.211.55.11), routing table information (two entries one for default network (0.0.0.0/0) with default gateway as 10.211.55.1, and one for locally connected network 10.211.55.0/24) and ARP entries (one entry for default gateway 10.211.55.1). Use the command below to find these information

H2 > `ip -4 addr show`

```
1: lo : <LOOPBACK,UP,LOWER_UP> mtu 65536 qdisc noqueue state UNKNOWN group default qlen 1000
   inet 127.0.0.1/8 scope host lo
      valid_lft forever preferred_lft forever
2: enp0s5: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1500 qdisc fq_codel state UP group default qlen 1000
   inet 10.211.55.11/24 brd 10.211.55.255 scope global dynamic noprefixroute enp0s5
      valid_lft 1506sec preferred_lft 1506sec
```

H2 > `ip -4 route show`

```
default via 10.211.55.1 dev enp0s5 proto dhcp metric 100
10.211.55.0/24 dev enp0s5 proto kernel scope link src 10.211.55.11 metric 100
169.254.0.0/16 dev enp0s5 scope link metric 1000
```

H2 > `arp -an`

? (10.211.55.1) at 00:1c:42:00:00:18 [ether] on enp0s5

f. Launch wireshark on H1 and capture traffic for H2, and launch wireshark on H2 to capture traffic for H1.

g. From H1 (10.211.55.10), send two ping packets to H2 (10.211.55.11) using the command below

H1 > `ping -c2 10.211.55.11`

h. Verify ping command is successful i.e. H1 receives ping response.

i. Analyze the ARP table on H1. It should show ARP entry for H2.

H1 > `arp -an`

j. Analyze the ARP table on H2. It should show ARP entry for H1.

H2 > `arp -an`

k. Using wireshark, verify the ARP broadcast request from H1 (10.211.55.10) to know who is 10.211.55.11 and ARP unicast reply from H2 (10.211.55.11) to H1.

**Learning**: Working of ARP protocol for delivering packets in locally connected network.

**Exercise 2**

**Topic**: Routing and delivery of packets when two networks are connected by intermediate routers.

a. Create a new network 10.1.2.0/24 and assign 10.1.2.1/24 in this network to ethernet interface of H1.

H1 > `sudo ip addr add 10.1.2.1/24 dev enp0s5`

b. Create a new network 10.1.4.0/24 and assign 10.1.4.1/24 in this network to ethernet interface of H2.

H2 > `sudo ip addr add 10.1.4.1/24 dev enp0s5`

c. Since both H1 and H2 now connects two networks and thus can act as routers. Enable routing functionalities in these multi-homed hosts using the following command. (Please note there should not be any SPACE character before and after ‘=’ (equal) sign.

H1 > `sudo sysctl -w net.ipv4.ip_forward=1`

H2 > `sudo sysctl -w net.ipv4.ip_forward=1`

d. Make a routing entry for network 10.1.2.0/24 (connected via H1) in the routing table of H2.

H2 > `sudo ip route add 10.1.2.0/24 via 10.211.55.10 dev enp0s5`

e. Make a routing entry for network 10.1.4.0/24 (connected via H2) in the routing table of H1.

H1 > `sudo ip route add 10.1.4.0/24 via 10.211.55.11 dev enp0s5`

f. Run wireshark on both H1 and H2 and capture traffic respectively for 10.1.2.1 and 10.1.4.1.

g. From H1, sending two ping packets to newly assigned 2nd IP address of H2 (10.1.4.1)

H1 > `ping -c2 10.1.4.1`

h. From H2, sending two ping packets to newly assigned 2nd IP address of H1 (10.1.2.1)

H2 > `ping -c2 10.1.2.1`

i. Both ping requests should be successful.
j. There should not be any new ARP entries in the ARP Table. \( H_1 \) would have ARP entry for \( H_2 \) (10.211.55.11) as gateway for network 10.1.4.0/24, and \( H_2 \) should have ARP entry for \( H_1 \) (10.211.55.10) as gateway for network 10.1.2.0/24.

k. Analyze the ping packets in wireshark captures and verify the source and destination IP addresses as well as source and destination MAC addresses.

l. Remove the routing entries created above in 4th and 5th step.

\[ H_1 > \text{sudo ip route del 10.1.4.0/24 via 10.211.55.11 dev enp0s5} \]

\[ H_2 > \text{sudo ip route del 10.1.2.0/24 via 10.211.55.10 dev enp0s5} \]

m. Send the ping packets again from \( H_1 \) to 10.1.4.1 and from \( H_2 \) to 10.1.2.1. Both pings should fail. This demonstrates the need of proper routing table to send packets.

**Learning:** Use of routing table in forwarding the packets.

### Exercise 3

**Topic:** Use of route summarization

a. Create a new network 10.1.3.0/24 (that can be route summarized with 10.1.2.0/24) and assign 10.1.3.1/24 in this network to loopback interface lo (or alternately to the ethernet interface enp0s5).

\[ H_1 > \text{sudo ip addr add 10.1.3.1/24 dev lo} \]

b. Create a new network 10.1.5.0/24 (that can be route summarized with 10.1.4.0/24) and assign 10.1.5.1/24 in this network to loopback interface lo (or ethernet interface).

\[ H_2 > \text{sudo ip addr add 10.1.5.1/24 dev lo} \]

c. Create route summarization entry 10.1.2.0/23 corresponding to two networks 10.1.2.0/24 and 10.1.3.0/24 in \( H_2 \).

\[ H_2 > \text{sudo ip route add 10.1.2.0/23 via 10.211.55.10 dev enp0s5} \]

d. Create route summarization entry 10.1.4.0/23 corresponding to two networks 10.1.4.0/24 and 10.1.5.0/24 in \( H_1 \).

\[ H_1 > \text{sudo ip route add 10.1.4.0/23 via 10.211.55.11 dev enp0s5} \]

e. Send ping packets from \( H_1 \) to both new network IP addresses of \( H_2 \). \( H_1 > \text{ping -c2 10.1.4.1} \)

\( H_1 > \text{ping -c2 10.1.5.1} \)

f. Send ping packets from \( H_2 \) to both new network IP addresses of \( H_1 \).

\( H_2 > \text{ping -c2 10.1.2.1} \)

\( H_2 > \text{ping -c2 10.1.3.1} \)

g. All pings should be successful. Analyze the ping packets in wireshark captures w.r.t. their source and destination IP addresses.

h. Remove the routing entry in \( H_2 \) as created in 3rd step above.

\[ H_2 > \text{sudo ip route del 10.1.2.0/23 via 10.211.55.10 dev enp0s5} \]

i. Resend the ping packets (5th and 6th step). These pings should be unsuccessful. From \( H_1 \), packets will reach \( H_2 \) (verify in wireshark capture) but \( H_2 \) does not have routing entries for reply packets. Similarly, \( H_2 \) will not send Ping request packets to \( H_1 \) because of no routing entries. A close analysis in wireshark will show that both these packets follow the default route i.e. these will go to gateway 10.211.55.1 which will be discarded, since these can't be delivered.

**Learning:** Use of route summarization to reduce the number of routing entries.

### Exercise 4

**Topic:** Use of Longest Prefix Match

a. Repeat the steps a. to f. from Exercise 2 i.e. assign IP address 10.1.2.1/24 to network interface enp0s5 of \( H_1 \), and IP address 10.1.4.1 to network interface enp0s5 of \( H_2 \), create corresponding routing table and check reachability.

b. Assign IP address 10.1.2.65/26 to network interface enp0s5 of \( H_2 \). Ensure to use the subnet mask /26 which makes a subnet of the network 10.1.2.0/24 belonging to \( H_1 \). So essentially, for \( H_2 \), aggregated network 10.1.2.0/24 is reachable via \( H_1 \), but its small subnet 10.1.2.64/26 is connected via \( H_2 \).

c. Similarly, assign IP address 10.1.4.129/27 to network interface enp0s5 of \( H_1 \). Please use the subnet mask /27 which makes a subnet of network 10.1.4.0/24 belonging to \( H_2 \). Essentially, for \( H_1 \), aggregated network 10.1.4.0/24 is reachable via \( H_2 \), but a small subnet 10.1.4.128/27 of it is connected via \( H_1 \).

d. Thus, if from \( H_2 \), when IP address 10.1.2.65 is pinged, the longest prefix match will send the packet locally to \( H_2 \) and this packet will not go to \( H_1 \). However, when IP address 10.1.2.1 is pinged, packet will actually go out on the network interface and reach \( H_1 \) and response will be received. Issue
the following ping commands and verify these are successful.

\[
\begin{align*}
H_2 & \text{ > ping -c2 10.1.2.65} \\
H_2 & \text{ > ping -c2 10.1.2.1}
\end{align*}
\]

e. Analyze the wireshark capture and verify working of longest prefix match.

f. Similarly, from H_1, send ping packets to 10.1.4.129 and 10.1.4.1 and verify working of the longest prefix match.

\[
\begin{align*}
H_1 & \text{ > ping -c2 10.1.4.129} \\
H_1 & \text{ > ping -c2 10.1.4.1}
\end{align*}
\]

g. Analyze the wireshark capture and explore working of the longest prefix match.

**Learning:** Use of longest prefix match in routing table to route the packets correctly even when multiple match occurs in routing table.

**References**


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**Prof. Ram P. Rustagi**

Dr. Ram P. Rustagi is currently working as Professor, CSE dept, KSIT Bangalore, and honed up his academic skills with Ph.D from IIT Delhi, and M.Tech from IISc Bangalore. Prior to KSIT, at Cavisson Systems, he mentored new technology development using Machine Learning techniques in Security and Performance Monitoring. At PES University, he had taught Undergraduates, Post Graduates students, and successfully guided 3 Ph.D scholars. At PESU, he brought innovations in teaching computer network and security courses, and introduced practical experiential learning exercises.
I have known Joy’s birth family since the 1970s. Our parents were close neighbors and good friends for over three decades in Bangalore, Karnataka, India.

I did not directly witness Joy’s academic highlights at St. Joseph’s Indian High School, Bangalore - I was almost a generation older and working in the Indian Navy. But I heard many stories. His classmates recollect how he arrived at simple and brilliant alternate solutions to those in the ‘Aggarwal Classes Notes’ - the gold standard prep for IIT JEE preparations in that era. Joy’s All India First Rank in IIT JEE, while still in the 11th class did not come as a surprise. He joined IIT Madras for a B.Tech. program and easily became a legend there too. He got a perfect score in GRE and moved to Stanford University in 1984 for his Ph.D. I was then, a visiting researcher at the university, on assignment from the Indian Navy. I was happy to welcome Joy to Stanford, this brilliant boy who grew up 100 feet down the street from my parent’s house in Bangalore.

Joy chose Prof. Tom Cover, a legend in Information Theory, as his Ph.D. advisor. Some years later, Joy joined Prof. Cover, who had waited for decades for a partner with Joy’s level of genius, as a collaborator on a definitive textbook on Information Theory, an important, though abstract, subject.

Their book, “Elements of Information Theory” is regarded by many as the benchmark text on Modern Information Theory, and a masterpiece for clarity of concepts and the simplicity of exposition. Now, in the second edition, it remains the most popular and admired textbook on this subject around the world. There is no good academic bookstore in the world without Joy’s book. And 10,000s of Ph.D. students have learned Information Theory from his book.

After Stanford (1990), Joy joined IBM Research and later did two successful startups in the Silicon Valley-Stratify (1999) and InsightsOne (2011), acquired by Apigee in 2014, which in turn was acquired by Google in 2016. He continued making seminal contributions to Predictive Analytics, working at Google, till his passing.

Joy was perhaps the most brilliant gift from India to the US in engineering sciences in recent decades. His loss is mourned by all the giants in Information Theory around the globe, from Stanford, MIT, Princeton, Berkeley, and ETH Zurich to mention a few. He will also be greatly missed in the Information Theory research community.

As a human being, Joy was gifted with wonderful qualities. Joy was a gracious and generous person. A loving father who doted on his two children Joshua and Leah, a devoted husband to his wife Priya, and to the rest of us, a caring friend who gave us strength in time of trouble, wisdom in time of uncertainty, and sharing in time of happiness.

Joy indeed had every gift, except the gift of long years. We all loved and admired Joy and the void left in our lives by his sudden loss can never be filled.

May his soul rest in peace.

A Tribute by Dr. Arogyaswami Paulraj, Professor Emeritus at Stanford University. He is the inventor of MIMO wireless communications, a technology breakthrough that enables improved wireless performance. Paulraj has authored/co-authored over 400 research papers, two textbooks and is a co-inventor in 80 US patents. Paulraj has won several awards, notably the 2018 US Govt. Patent and Trademark Office’s National Inventors Hall of fame, 2014 Marconi Prize and Fellowship and the 2011 IEEE Alexander Graham Bell Medal. He has also received the prestigious Padma Bhushan in India.
Why do I call "Groundbreaking Inventions in ICT" a great book? Firstly, because it deals with a very important topic – the revolution that changed our lives. The book helps us celebrate the IT revolution. The last fifty or sixty years have been a great time. Something similar to the Industrial Revolution. However, everyone did not recognize what was happening in the early years of the revolution. I had asked my college principal to be allowed to change to another college so that I could study electronics. He did not allow me to do that. "First complete the BE in electrical engineering you are doing," he said, "then you can be sure of a job. With electronics and all that, who knows? You might be hunting for a job!" He gave me a concession though; "You can do a master's degree course in electronics after your BE, if you want to!"

Let us talk about economic growth. I will borrow some statistics from sources other than Professor's book. The World (nominal) GDP has gone up from roughly 11 Trn to 80 Trn $ over the last 60 years. It has grown faster than the world population. Researchers estimate that "the digital economy is worth $11.5 trillion globally, equivalent to 15.5 percent of global GDP and has grown two and a half times faster than global GDP over the past 15 years."

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output [1] by the World Bank group. In which year was this the case? Take your pick. It was 4% in 2010. It was 4% in 2019. Compare that with the IT Sector.

What made the difference to the poor students of electronics and computer science who had missed the good advice from my Principal?

Much of the difference was due to the fifteen great ideas that this book describes.

The growth I refer to did not leave India behind. India was the tenth ranker in the world in terms of GDP in 1960. By 2019 it had moved to the 5th rank. Where has the growth come from? And was the growth supported by IT – did it help only the electronics and computer science graduates? Of course not! The benefits have been fairly well spread out.

There is something special about information technology. All along the world has been understood in terms of space and time, matter and energy. The recognition that information is another essential entity was a great step forward. Much of science had been natural science. The rise of the sciences of the artificial has been a major step forward too. The book helps us understand the key ideas in information technology. The selection of ideas has been obviously difficult. Some great ideas have been set aside for the successor to the book.
Medical imaging, speech recognition, face recognition, natural language I get reminded of the saying that the engineer is the guy who knows how to get things done, and the manager is the guy who tells engineers what to get done. My former boss Mr. N Vittal, at that time Secretary to Govt. in the Dept. of Electronics, used to be asked “Aap electronics engineer hain kya?”. Mr. Vittal’s answer used to be “Nahi. Hum Electronic Engineer ka Baap hain!” He would explain that his son was an electronics engineer! Prof. Rajaraman’s book deals with the things that managers understand and value in addition to the technical stuff.

Great institutions do things in style. They have high standards and confidence in acting as per these standards. Prof. Rajaraman tells the story of a young man at Harvard who is getting ready to receive his Ph.D. The date is set, the family has been informed. He has been offered a job and has accepted it, but advisory committee rejected his thesis at the last minute. The young man calls his boss on the west coast and says, “My Committee has failed me saying ‘mostly implementation, not enough maths’. The manager says ‘Join us anyway, and complete your work here adding what they want’.” The manager was at Xerox Park at Palo Alto and the young man was Bob Metcalfe, one of the inventors of Ethernet.

Then there is the story of a couple of students who decide to drop out before getting their degree. Their professor encourages them, putting some of his own money into their start-up which grows up in time to be world’s largest Internet company with a market cap of 741 Billion$. By the way, says Prof. Rajaraman, the Professor concerned had been a graduate of the first batch of the Computer Science Dept. of IIT Kanpur! The Institution from which the students had dropped out was Stanford! These stories are merely two examples. There are many more in the book. We learn as much from these stories as we do from the technical ideas.

I will conclude by saying that this book is a rare one of its genre. The rarity of such books is one reason that we in the engineering community do not read as much as we should. Our scientific colleagues are much better off. There are so many books on the history of science. That reminds me of the time I was in the selection committee to identify a Vice President for an IT company. I asked a candidate if he could name a good book he had read in the past year. He looked puzzled and worried. Then he managed to name a book – it was MySQL Reference Manual! That raises the question of what is a good book! Then we can ask what is a great book!

Now you know.

References


Quoted by Brookings Institution in https://www.brookings.edu/research/trends-in-the-information-technology-sector/

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Srinivasan Ramani

Dr. Ramani was Research Director, HP Labs India, located in Bangalore. He founded the National Centre for Software Technology (NCST) in 1985, and had directed it during 1985-2000. His work at NCST covered R & D in the areas of computer networks and knowledge based computer systems. He made significant contributions to the creation and development of the Indian academic network, ERNET, which brought Internet connectivity to India in 1988, and the Bombay Library Network, Bonet. He has served as Editor, Journal of Information Technology for Development, for a number of years.

He was President, International Council for Computer Communication, and Chairman of the Governing Board of the Information Library Network (INFLIBNET). He was also a member of the High Level Panel of Advisors to the UN on Information and Communication Technologies.
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