**Advanced Computer Networks**
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**Lecture 23**
**Introduction to Network Softwarization**

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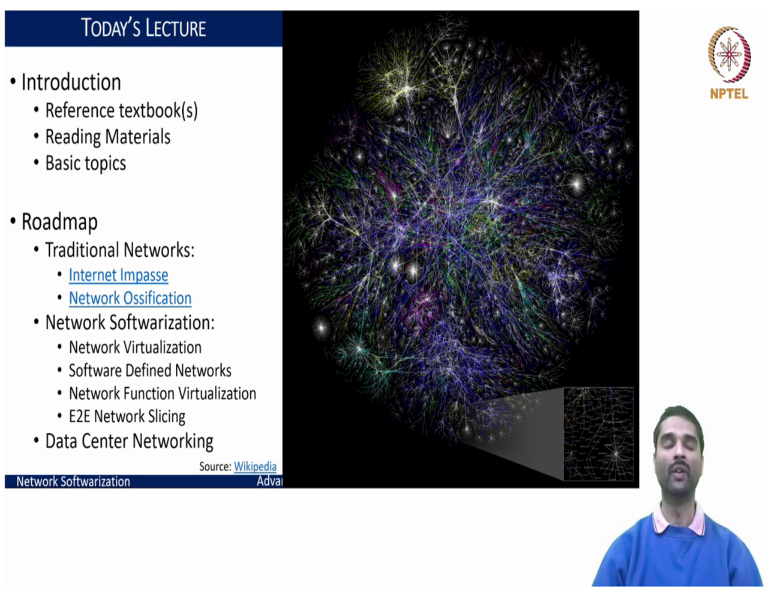


Namaste, and welcome to the course on Advanced Computer Networks. I am Sameer Kulkarni. I am a faculty in the discipline of Computer Science and Engineering IIT Gandhinagar.

The picture on the right side of this slide is our universe in the scopes. What I mean by this is that all the content that we are going to cover stems from what we are looking at this picture. And you might have guessed by now that this picture is exactly a snapshot of the internet. And this snapshot was taken long back, around 2008. However, it already looks so complex, Right? And the colors here in this picture represent the different internet domains, and the vertices represent the servers that serve the internet content to you. And this is exactly what we will learn and understand what it means to make such an internet architecture and what were the challenges thereon, and how the networking or the research community has tried to address these concerns.

So the roadmap of our learnings looks somewhat like this. So that we begin with the traditional networks and try to understand what the networking community or the researchers termed as internet impasse and network ossification. Thereafter, we will try to look into the approaches that were taken to deossify and disentangle the internet impasse through the concept of softwarization. And then we will learn about the key aspects of softwarization including network virtualization, software-defined networks, network function virtualization, and potentially end-to-end network slicing in the case of 5G. And then, we will switch gears and try to understand the next aspect that is data center networking. And data centers are, in fact the core infrastructure or the real enablers of the cloud computing or the edge networks that are going to come in the era of 5G and 6G.

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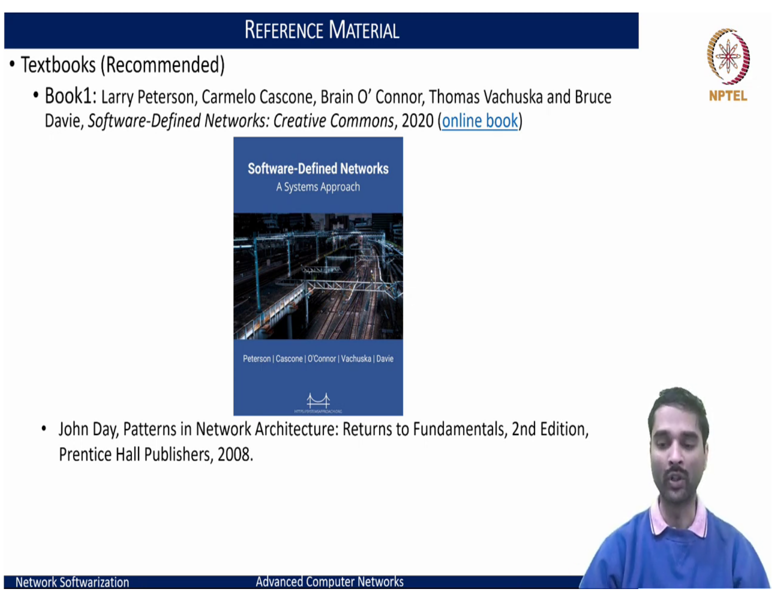

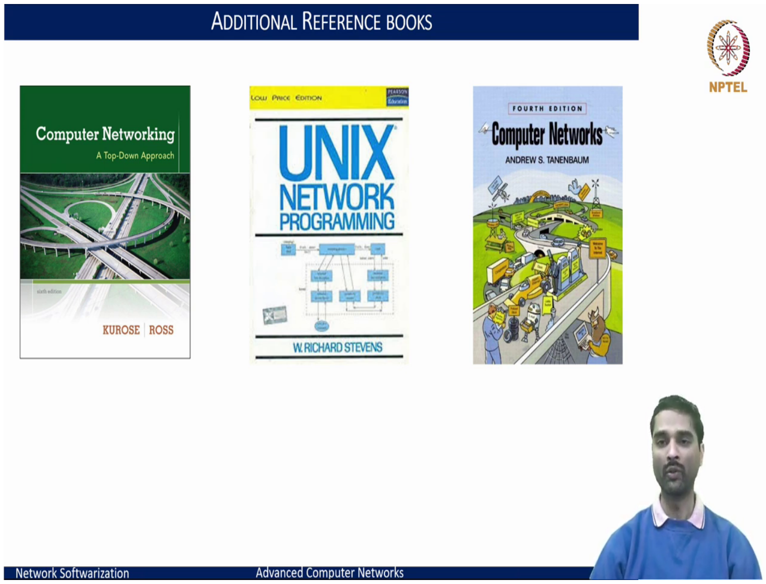


But before we begin our today's topic, let me quickly introduce you to the course of material that would come handy for you. And the textbook that I have shown here, Software-Defined Networks, a systems approach by Larry Peterson and Bruce Davie, would be the most relevant book for the following lectures in SDN. Note, however, that we will not be covering this textbook in its entirety. Only certain bits and pieces relevant for the scope of software-defined networking would be addressed.

Also, if you are a systems design or architecture enthusiast, I would recommend this book, Network Architecture Return to Fundamentals by John Day. As you will find, it is interesting and insightful to understand the networks and evolution from the architectural point of view and where things have gone wrong, and where things have been right. But this will not be the scope for our course. And I also expect that you would have already gone through one of these basic undergraduate-level networking textbooks, like Computer Networking by Kuros and Ross, or Computer Networks by Andrew Tanenbaum. And I assume most of the concepts on the networking that these textbooks offer would have been covered by you in your earlier undergrads course. If you are interested in learning about how to develop network stacks or build the TCP/IP stack, the way it is in the Unix or Linux systems, the book on Richard Stevens would be very useful.

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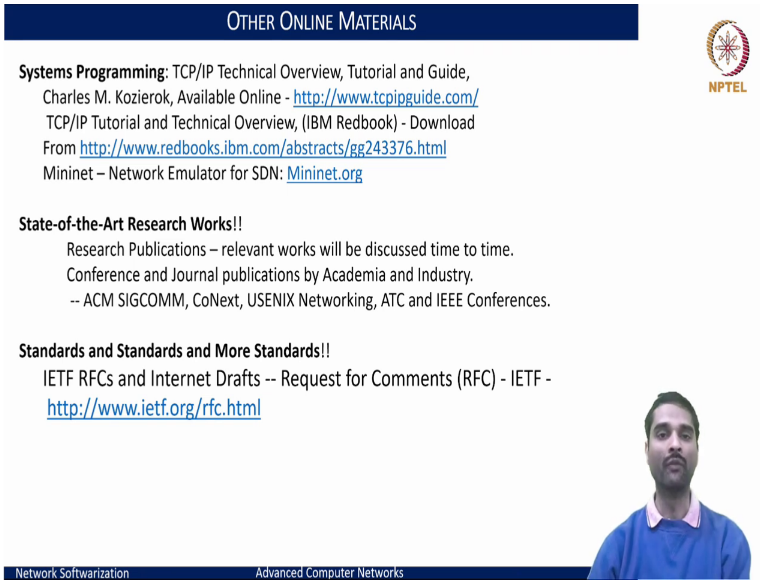


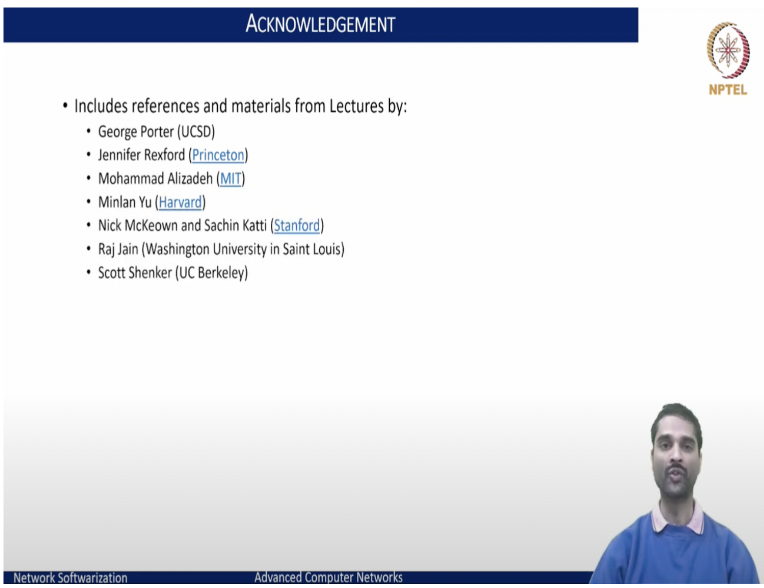


I have also listed here some of the important online materials that may be of use to you at later stages of this course, especially the mininet or network emulator for the SDN, where we are going to cover certain topics and do some hands-on, provided we have enough time, and also have you do some work as assignments on this. And as we go along, we will also be covering several of the important research publications from both academia and industry that have influenced and shaped computer networks. And in my personal opinion, I consider learning computer networks would be incomplete without the readings of the Internet Engineering Task Forces – Request For Comments on the Internet and the Internet drafts. So I also plan to cover and point certain relevant internet drafts as we go along.

And lastly, and most importantly, I would also like to acknowledge that the lecture materials that I am going to present here in the course of next five weeks is built from the lecture materials from the following sources.

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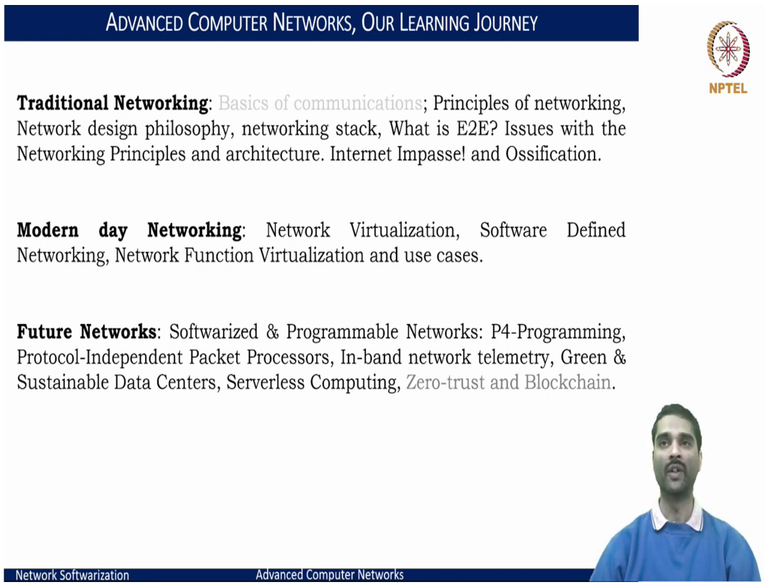


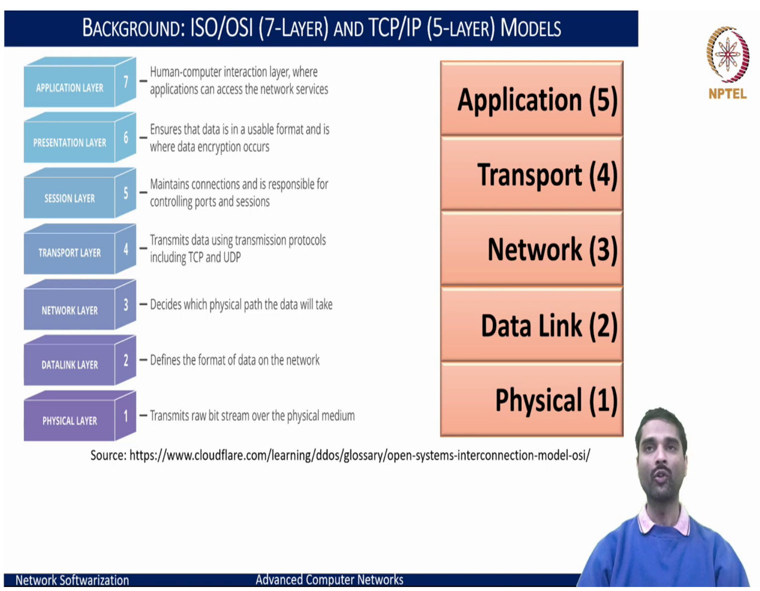

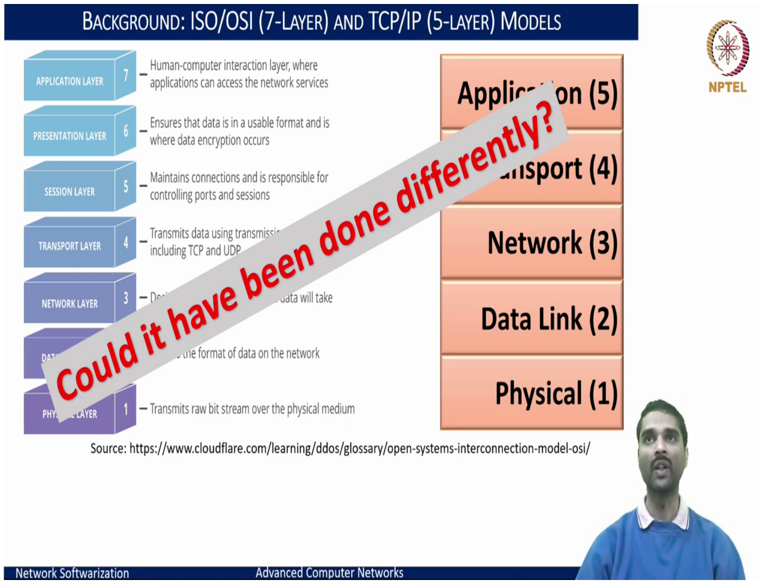


Okay, to quickly summarize what our learning journey looks like. As I said, it is essential, to begin with traditional networking and not in terms of the concepts on what the network is built, but the key principles and the design philosophy behind building such a network stack and what it means as an end-to-end argument in networking. And then look into the key issues that align due to the evolution of the network following or not following specific principles and understand these terms of internet impasse and ossification

Next, we will look into the modern-day networking that we plan in the view of the softwarized networks, considering network virtualization, software-defined networking, network function virtualization, and the associated use cases. And then, in the last phase of this course, we will look into the softwarized, not just the softwarized, but also the programmable networks, namely the P4 or programming protocol-independent packet processors. Thereafter, we will look into the real enablers of the cloud that is the data centers from the networking perspective.

And I take it for granted that we are all familiar by now with this seven-layer ISO/OSI model that is shown on the left side of this slide. And also the five-layer TCP/IP model shown to the right of this slide. But then you might have learned what the physical layer, data link layer, network layer, transport layer, and application layer do and the associated protocols to a great extent. But the key questions that I want to pose are the following. One, why is the stack built the way we see it? Now, in terms of either the TCP/IP model or the ISO/OSI layer model, especially on what principles, if any was it built? And then, more importantly, we would also want to question and understand, could it have been done any differently? And to answer these questions we would have to step back a bit and peek into the history and understand the evolution of the computer networks.

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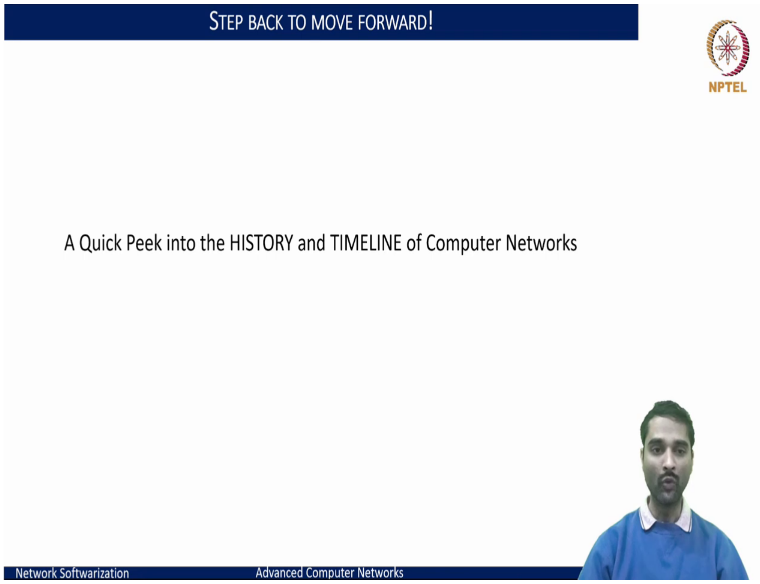


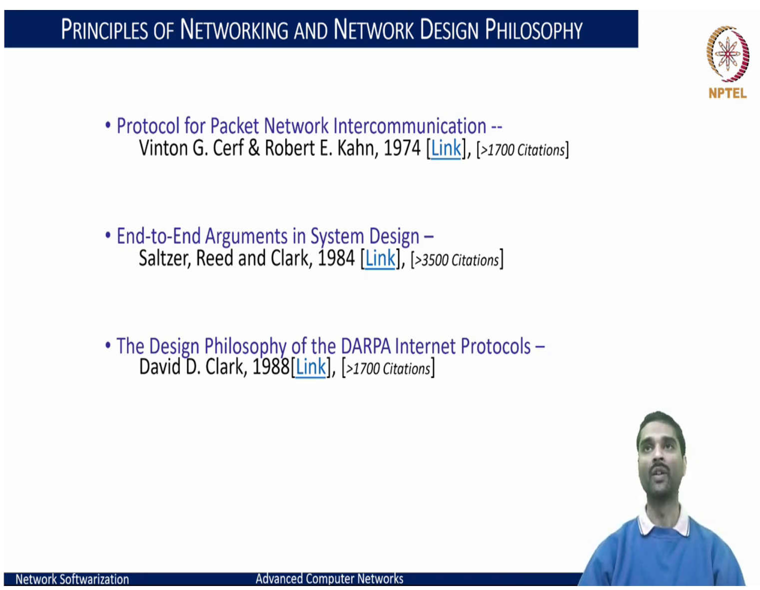


So let us try to do that in the view of evolution as well as the keywords that have influenced evolution. And first, in terms of the principles of networking and the design philosophy, I present to you the three papers here: The first is this paper from Vinton G. Cerf and Robert E. Kahn, who are considered the founding fathers of the internet. And this work in fact put forth the philosophy of internetworking and laid down the mechanisms for handling the aspects of addressing, routing, and the means to support multiple reliable connections over an unreliable connection on an unreliable network, the variations in the packet size, accommodation of fragmentation and flow control aspects.

And in fact, this is the first work that brought the notion of internet protocol or, in a clear sense, one protocol as the center of the hourglass. And we will speak about this in greater detail as we go forward. And then the two other papers, the end-to-end arguments in system design, which is the most cited work as you can see roughly it has garnered more than 3500 citations. And the reason being that is the core principle that theorized what it means to provide the functionalities for the network. We will look into this in detail as we go.

And the other core work by David Clark, in terms of the design philosophy of the DARPA internet protocols, more a reflection as well as what are the supposed suggestions of how the internet protocols have to be. And this work fundamentally put forward a lot of objectives for the internet protocols. And these objectives as primary and secondary values and were put forth to say what should be the key role of the Internet. And it stems from this work that the primary goal for the internet is always the reliability and survivability of communications, and it needs to support multiple heterogeneous networks to operate and work together. And these were preferred over cost efficiency and accountability.

And as a result of these, what we now have an internet is not a centralized entity, but a decentralized and distributed collection of networks. And across all these works, what we also see in common is in the design of the internetwork or internet, the most important emphasis has been on simplicity is preferred over complexity. And as a result, instead of having the mechanisms in IP to make sure that packets are delivered correctly, we see the burden being pushed to the end hosts and IP of the network layer being as simple and just being the best-effort service. And all of these design criteria together have led to this highly decentralized internet architecture, which by the way is somewhat reliable but not as much accountable.

And another important aspect also comes along in the design of the internet is the fate-sharing concept that was put forth in the design philosophy of the DARPA internet protocols, where the concept is all about saying that either you fail in all or work together. So that whenever there is a failure, everyone fails. And this is exactly an example of how the end-to-end principle operates.

And also the concept of saying that the information or the state better be stored on the end hosts rather than at the transport layer or in the network.

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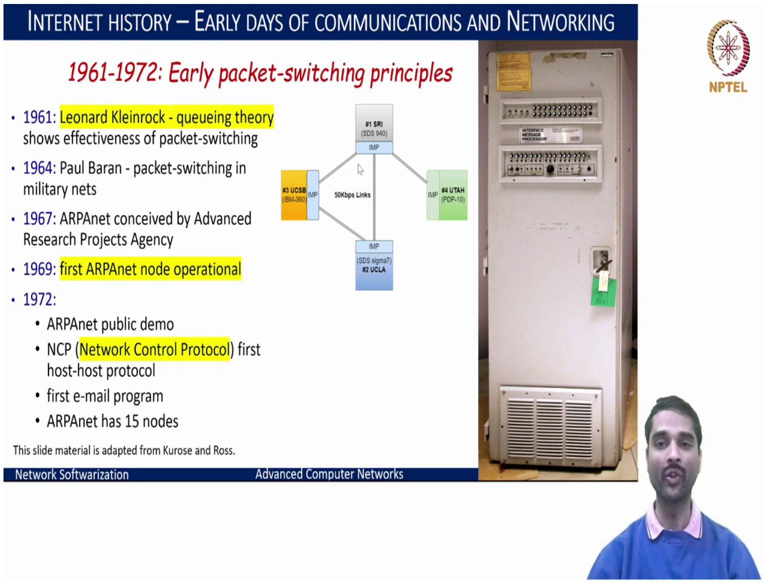


So let us look at this evolution in greater detail. The internet, or rather the quest for networking, started way back in 1960s. And this was a way for government researchers to share information. And if we look back at the 1960s, the computers then were very large and almost immobile. And when I say large, it used to be like the mainframe computers that would occupy room of a large size. And that made them definitely immobile to move the information. And the only way that the information could be moved or obtained from a particular machine would be that either you travel to the site and get access to that mainframe computer or have the magnetic tapes through which you can backup the content and send it over the post.

And there were these very reasons that made people think of alternatives to share the information. And the US Defense Department, which was a pioneer in looking at these alternatives, eventually led to the formation of the ARPAnet or the Advanced Research Projects Agency network. And the whole aim then was the sharing of the information that can be done through the network. And during these times, the professors at various places were also looking for building these networks.

Donald Davies at the National Physics Laboratory in UK, Paul Baran at Rand Corporation, USA, and Leonardo Kleinrock, who was then MIT PhD student, were looking forward to the packet-switched networks. And the work by Leonardo Kleinrock showed the effectiveness of the packet-switching network, and this fundamentally laid down the aspects of what we defined today's internet, which is a packet-switched network. And those evolutions of the packet-switched network stand back to the days, early days of the 1960s when the ARPAnet started to operate. The first ARPAnet operational node was achieved in December of 1969.

And what we achieved was exactly this four-node network that you are seeing on this slide here. The first node was at Stanford Research Institute, and this node was basically a mainframe SDS 940, which was a 24-bit mainframe system. And the second node was at UCLA, made of the SDS Sigma7 mainframe system, which was a 32-bit mainframe device. And the third node was located at UC Santa Barbara. And we ran the IBM Systems 360-75 mainframe. And this was a 32-bit machine. And the fourth node was at Utah, University of Utah, which ran the PDP-10 mainframe device and interestingly, this machine was a 36-bit machine.

So you can see the heterogeneity, where a 124-bit machine at Stanford Research Institute, a 36-bit machine at the University of Utah, and two 32-bit machines at UCLA and UCSB, were all connected to make a first four-node network. And the backbone connections were made using the 50 kilobits per second links laid down by AT&T, which is nowhere near to what we look at today's network of more than one gigabits to several gigabits per second links.

Interestingly, you would also see a processor called the interface message processor, which was exactly what we call today as the network gateways or the routers. And you can see this fridge-like device here sitting there to facilitate that communication. So this was added on to these mainframes to facilitate this network communication. So now we imagine this versus a router that you can hold in your hand. So that is the evolution that we are speaking about. And nonetheless, all of it started with these kinds of devices. And then the first protocol for facilitating this communication, called the network control program or backported to say network control protocol happened to exist to make this network's devices to talk. And as one would say, the first connection that was tried on this was between SRI and UCLA.

And as we would have, it crashed the moment the third character was transmitted. And apparently, the login was the first word that was tried to be transmitted. And as soon as it got the third character G, the device at SRI crashed, and they had to restart the machine to get it working. But nonetheless, it succeeded, and then that laid to the first operational networks. And thereafter this network evolved, and over the years by 1972, the ARPAnet reached around 15 nodes spanning several of the universities in the US.

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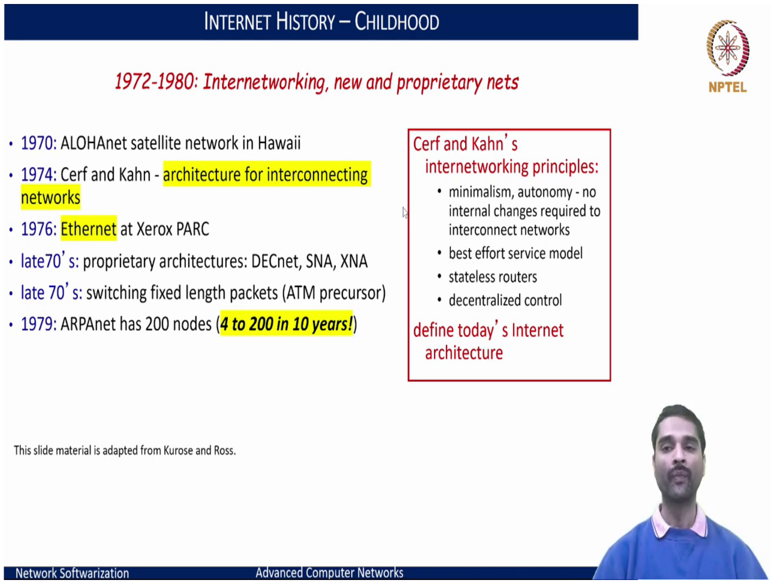


And then revolution continued, and in the era of 1970s to 1980, several of the internet or the networking principles came out, and the main is this Cerf and Kahn's work that laid down the key internetworking principles, which can be summed up as saying the internetworking should be based on minimalistic approach with no autonomy whatsoever. And by the sense of autonomy, we mean the changes that are required to interconnect networks should not be owned by one entity. And what this also meant is to facilitate and support the evolution of heterogeneous networks. And the whole role of the network needs to be the best effort service model in that once it takes the data, it tries to do its best to deliver the data to the other end and not have any state embedded in the networks that is essentially the stateless routers and decentralized control. And these are the key founding principles that define today's internet architecture.

And also by 1976 ethernet was heard as what we know as IEEE 802.3 came out and led the way for internet-based connections. And there were also several proprietary architectures of networks that were proposed in computing TechNet, SNA, and XNA. Later several of the networks started to grow, and by 1979 we would have our ARPAnet grow around 200 nodes that is from 4 to 200 nodes in around 10 years.

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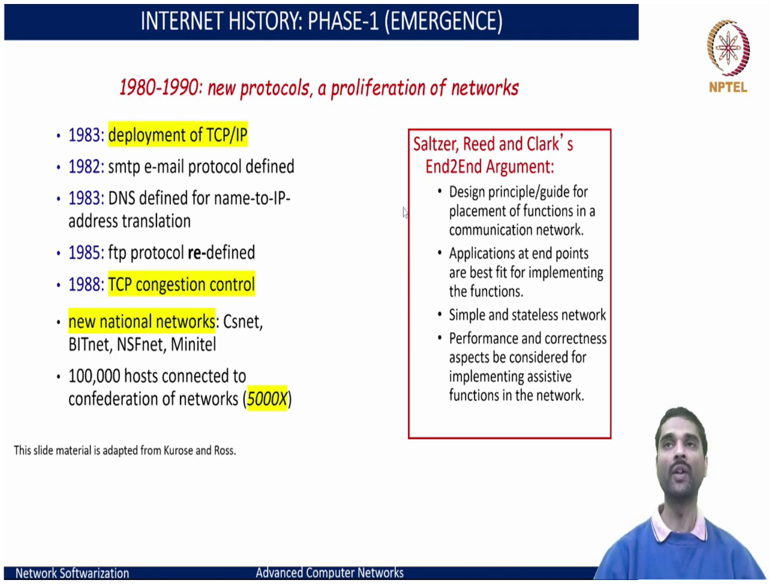


Thereafter the evolution continued, and lots of many things came to shape. And the most critical thing that really shaped today's internet is the arrival of the TCP/IP protocol stack in 1983. In fact, the foundations of the TCP/IP protocol stack were laid long back by the Vinton Cerf and Kahn paper. But the actual deployment happened on January 1st of 1983, which is also known as the flag day; networking went on to change to use the TCP/IP protocol and replace the earlier NCP protocol. And this is the only time in history where we have had a change that has occurred in just one day. And this is also the last of such things that to happen because the internet grew and it is no more feasible to change anything in one day. And the deployment of TCP/IP in fact led to the emergence of lots of new protocols.

And again, in 1983, the role of DNS in terms of how you would want to identify the IP and associate IP with the name or what was called address translation came into the picture. And then, around 1985, the FTP protocol was rather redefined. In fact, FTP has a very interesting history. Prior to Shri Abhay Bhushan, an alumnus of IIT Kanpur, introduced the FTP in April 1971 while he was pursuing his master's at MIT. And thereafter, it was reshaped to suit the TCP/IP model, and the new FTP was defined in 1985.

And then, the networks started to emerge, including national networks like Csnet, BITnet NFSnet, Minitel, and so on. And what really started to happen was the widespread usage, with more than 100,000 hosts connected to this configuration of networks. And in fact, when we scale a lot, we also started to see several anomalies in the operations of the network. And what was termed as the congestion collapse. That was the time when the internet hosts would send their packets, but the end hosts on the receiving end would never receive those packets due to the packet drops that used to happen at these intermediary router devices. And the hosts that were trying to send the packets would wait, and as they see no acknowledgment coming back, they would retransmit the packets leading to even worse congestion. And that is when during 1988, the work by Van Jacobson tried to address this congestion and provided the mechanisms for TCP to control the congestion and work through the congestion aspects and provide reliable communication.

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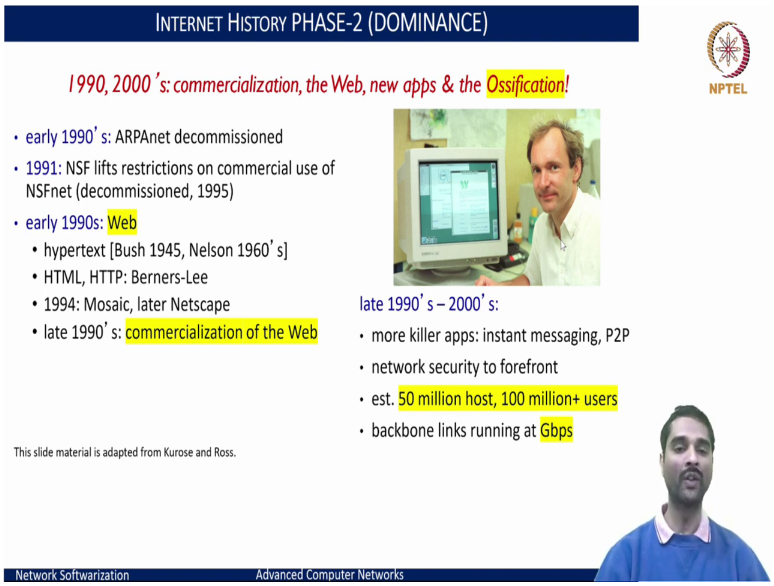


And all these aspects led to widespread usage of the Internet, and several of the internet applications started to emerge. And most notably, the one that has shaped the current internet to the most is the emergence of the web. Web or the world wide web, www is nothing but a system of interlinked hypertext documents that are accessed via the internet. And the web was originally conceived and developed to meet the demand for automated information sharing between the scientists in universities and institutes around the world. And this was the proposal that was put forth by Tim Berners Lee and his colleague Robert Cailliau in 1989 at Cern. And in this way, once the web gained popularity, there were no limits, and lots of new aspects started to shape the internet. And in 1994, we had the first Mosaic or the Netscape web browser, and thereafter the commercialization phase of the web or the internet started to take shape.

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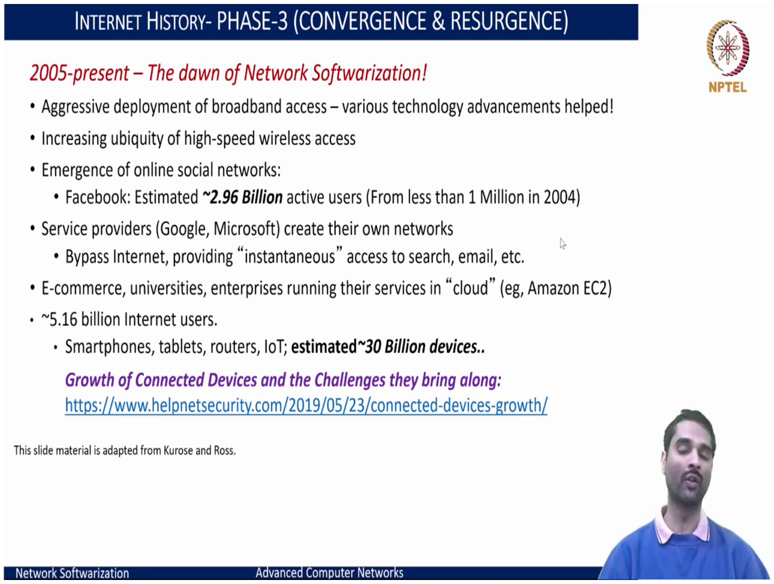



And with this, several technological advancements fostered the widespread adoption of the Internet. And just to give this aspect like the deployment of the broadband access started to take shape and high-speed wireless access also started to come into the picture, and all the high-speed gigabit ethernets were also becoming more and more prominent. And once it became accessible to most of the users, even the applications like Facebook, which was a social network at that time which started with roughly around a million users in 2004. And now if we estimate the scale spans to around roughly 3 billion active users today. And this shows the emergence of the Internet and the widespread scale that it has gone.

And in fact several of the service providers like Google and Microsoft started to create their own networks and provide several of these specific services like search email and the Google Classrooms that you would have used during the COVID times and you name them. There are many more services. Now we cannot think of a service without Internet. And including the services that universities, the e-commerce sites, all try to adopt the cloud as a notion which is not accessible without the sources of the network. And as I speak today, we have a world population of roughly 8 billion, but the internet population, and by internet population, I mean the users, the devices that are provided connected to the network including the infrastructure of the internet including the switches, the routers, and the middleboxes. The population of the internet is roughly 30 billion, so 3 to 4 times more than the world population.

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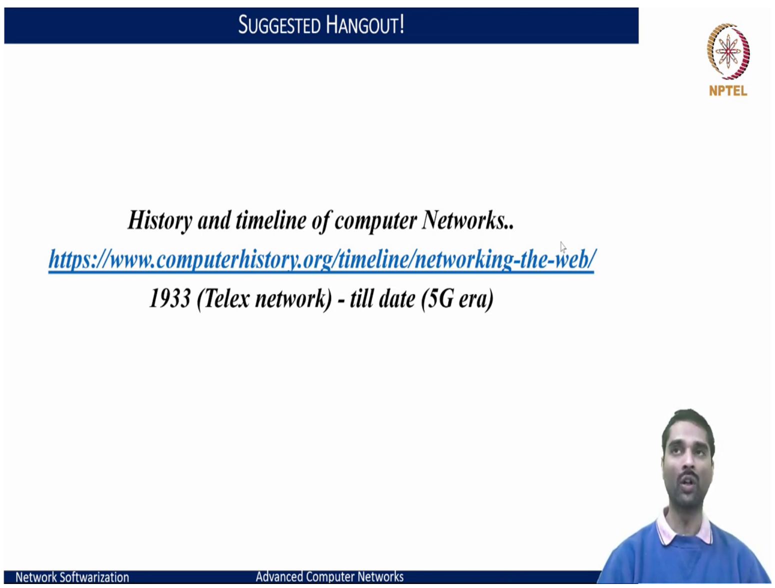


So definitely this internet growth which has spanned over more than 60 plus years, has hired its positives and negatives. And if you are interested in trying to learn more about each of the aspects of the evolution, I would recommend this website computerhistory.org, where the timeline of the networking, the web has been presented in greater detail, starting from the days of the Telex network in 1933 to the date of the evolution in the 5G era. And Telex in India was known as tar, the first modern electronic communication and payment system. And this was, however decommissioned in India a decade ago, around 2010.

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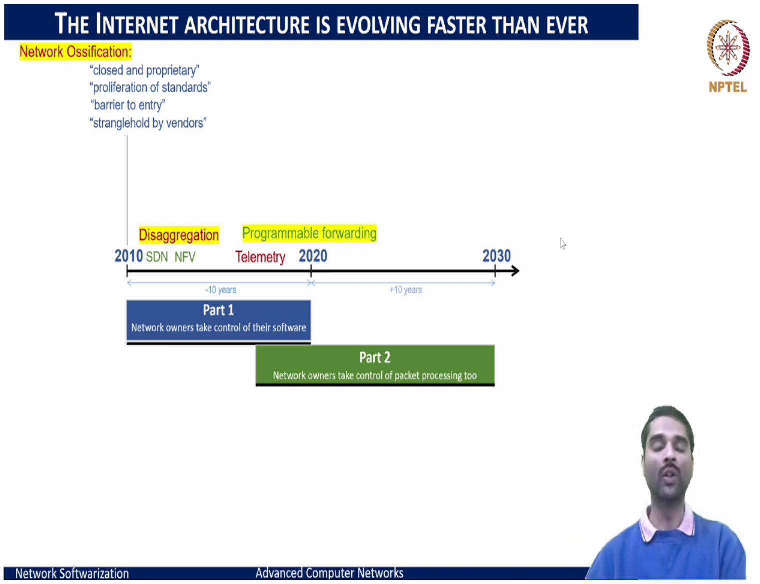


So, to sum up, we have looked at the internet's evolution, and we take it that Internet architecture is evolving faster than ever. And we consider this internet architecture for our simplicity into 3 phases the first pre-2010 where we call the network classification stage, where several of the closed and proprietary developments happened, several of the proliferation of the standards was done, but many became barriers for entry. And several of the stakeholders started to play prominent roles.

And the second phase, what I call as the disaggregation phase, where the network owners try to take control of the software, and this happened through the emergence and adoption of SDN and NFV. And the future or the third phase in terms of what I call programmable forwarding, where the network owners not only take control of the software but also control the way the packets would be processed for them, in terms of having the ability to program precisely what the network needs to do for them rather than relying on the network or third party software or vendors to dictate what the network would do.

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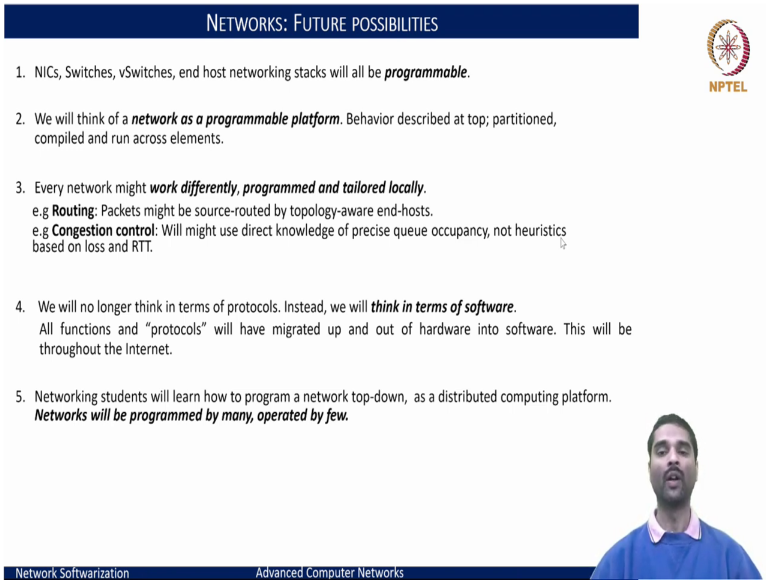


So to think of we may consider the future possibilities of networks being completely programmable and networks to emerge as a programmable platforms in the sense that every end user would have the control to dictate and program the way the networks would want to be operated for them. And network there on we can think in terms of the software and consider that there will be these networks as software be programmed by many and operated or basically managed by a few to enable their custom requirements.