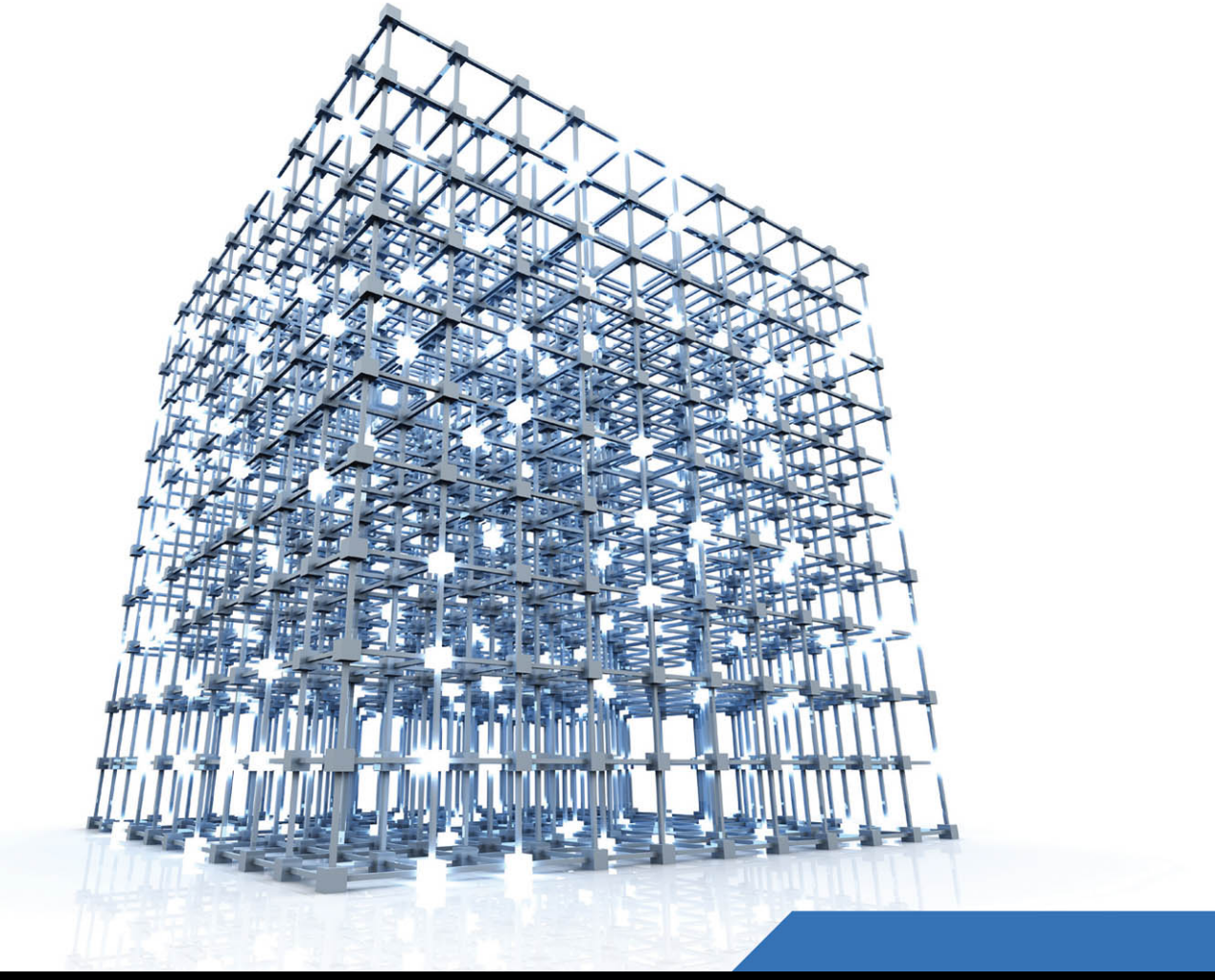
William Stallings

Foundations of Modern Networking

SDN, NFV, QoE, IoT, and Cloud



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Foundations of Modern Networking

SDN, NFV, QoE, IoT, and Cloud

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About the Author

Dr. William Stallings has made a unique contribution to understanding the broad sweep of technical developments in computer security, computer networking, and computer architecture. He has authored 18 textbooks, and, counting revised editions, a total of 70 books on various aspects of these subjects. His writings have appeared in numerous ACM and IEEE publications, including the *Proceedings of the IEEE* and *ACM Computing Reviews*. He has 13 times received the award for the best computer science textbook of the year from the Text and Academic Authors Association.

In over 30 years in the field, he has been a technical contributor, technical manager, and an executive with several high-technology firms. He has designed and implemented both TCP/IP-based and OSI-based protocol suites on a variety of computers and operating systems, ranging from microcomputers to mainframes. Currently, he is an independent consultant whose clients have included computer and networking manufacturers and customers, software development firms, and leading-edge government research institutions.

He created and maintains the Computer Science Student Resource Site at ComputerScienceStudent.com/. This site provides documents and links on a variety of subjects of general interest to computer science students (and professionals). He is a member of the editorial board of *Cryptologia*, a scholarly journal devoted to all aspects of cryptology.

Dr. Stallings holds a Ph.D. from M.I.T. in Computer Science and a B.S. from Notre Dame in electrical engineering.

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Sofiene Jelassi received a Bachelor of Science and a Master of Science from the University of Monastir, Tunisia, in June 2003 and December 2005, respectively. He obtained a Ph.D. in Computer Science from the University of Pierre and Marie Curie, Paris, France, in February 2010. His doctoral thesis was titled *Adaptive Quality Control of Packetized Voice Conversations over Mobile Ad-Hoc Networks*. From June 2010 to December 2013, he worked as an R&D engineer at Inria within DIONYSOS research group. From January to December 2014, he worked as a post-doctoral fellow at GTA/ UFRJ in Rio de Janeiro, Brazil. Since January 2015, he has been working as Assistant Professor at University of Monastir, Tunisia. His research includes wired and wireless software-defined networks (SDNs), server and network virtualization, network monitoring, content-oriented management of mobile networks and services, mobile virtual network operators (MVNO), customized voice and video systems, quality of user experience (QoE) measurement and modeling, in-lab and in-field usability testing, crowdsourcing, user profiling, context sensing, service gamification, and social-driven emergency services. Dr. Jelassi has more than 20 papers published in international journals and conferences.

Dedication

To Tricia, my loving wife, the kindest and gentlest person.

Acknowledgments

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With all this assistance, little remains for which I can take full credit. However, I am proud to say that, with no help whatsoever, I selected all the quotations.

Preface

There is the book, Inspector. I leave it with you, and you cannot doubt that it contains a full explanation.

—*The Adventure of the Lion's Mane*, Sir Arthur Conan Doyle

Background

A host of factors have converged to produce the latest revolution in computer and communications networking:

- **Demand:** Enterprises are faced with a surge of demands that focus their attention on the need to design, evaluate, manage, and maintain sophisticated network infrastructures. These trends include the following:
  - **Big data:** Enterprises large and small increasingly rely on processing and analyzing massive amounts of data. To process large quantities of data within tolerable time periods, big data may need distributed file systems, distributed databases, cloud computing platforms, Internet storage, and other scalable storage technologies.
  - **Cloud computing:** There is an increasingly prominent trend in many organizations to move a substantial portion or even all information technology (IT) operations to an Internet-connected infrastructure known as enterprise cloud computing. This drastic shift in IT data processing is accompanied by an equally drastic shift in networking requirements.
  - **Internet of Things (IoT):** The IoT involves large numbers of objects that use standard communications architectures to provide services to end users. Billions of such devices will be interconnected in industrial, business, and government networks, providing new interactions between the physical world and computing, digital content, analysis, applications, and services. IoT provides unprecedented opportunities for users, manufacturers, and service providers in a wide variety of sectors. Areas that will benefit from IoT data collection, analysis, and automation capabilities include health and fitness, healthcare, home monitoring and automation, energy savings and smart grid, farming, transportation, environmental monitoring, inventory and product management, security, surveillance, education, and many others.
  - **Mobile devices:** Mobile devices are now an indispensable part of every enterprise IT infrastructure, including employer supplied and bring your own device (BYOD). The large population of mobile devices generates unique new demands on network planning and management.
- **Capacity:** Two interlocking trends have generated new and urgent requirements for intelligent and efficient network design and management:

- **Gigabit data rate networks:** Ethernet offerings have reached 100 Gbps with further increases in the works. Wi-Fi products at almost 7 Gbps are available. And 4G and 5G networks bring gigabit speeds to cellular networks.
- **High-speed, high-capacity servers:** Massive blade servers and other high-performance servers have evolved to meet the increasing multimedia and data processing requirements of enterprises, calling for a need for efficiently designed and managed networks.

- **Complexity:** Network designers and managers operate in a complex, dynamic environment, in which a range of requirements, most especially quality of service (QoS) and quality of experience (QoE) require flexible, manageable networking hardware and services.
- **Security:** With increasing reliance on networked resources, an increasing need emerges for networks that provide a range of security services.

With the development of new network technologies in response to these factors, it is imperative for system engineers, system analysts, IT managers, network designers, and product marketing specialists to have a firm grasp on modern networking. These professionals need to understand the implications of the factors listed above and how network designers have responded. Dominating this landscape are (1) two complementary technologies that are rapidly being developed and deployed (software-defined networking [SDN] and network functions virtualization [NFV]) and (2) the need to satisfy QoS and QoE requirements.

This book provides the reader with a thorough understanding of SDN and NFV and their practical deployment and use in today's enterprises. In addition, the book provides clear explanations of QoS/QoE and the whole range of related issues, such as cloud networking and IoT. This is a technical book, intended for readers with some technical background, but is sufficiently self-contained to be a valuable resource for IT managers and product marketing personnel, in addition to system engineers, network maintenance personnel, and network and protocol designers.

Organization of the Book

The book consists of six parts:

- **Modern Networking:** Provides an overview of modern networking and a context for the remainder of the book. Chapter 1 is a survey of the elements that make up the networking ecosystem, including network technologies, network architecture, services, and applications. Chapter 2 examines the requirements that have evolved for the current networking environment and provides a preview of key technologies for modern networking.
- **Software-Defined Networks:** Devoted to a broad and thorough presentation of SDN concepts, technology, and applications. Chapter 3 begins the discussion by laying out what the SDN approach is and why it is needed, and provides an overview of the SDN architecture. This chapter also looks at the organizations that are issuing specifications and standards for SDN. Chapter 4 is a detailed look at the SDN data plane, including the key components, how they

interact, and how they are managed. Much of the chapter is devoted to OpenFlow, a vital data plane technology and an interface to the control plane. The chapter explains why OpenFlow is needed and then proceeds to provide a detailed technical explanation. Chapter 5 is devoted to the SDN control plane. It includes a discussion of OpenDaylight, an important open source implementation of the control plane. Chapter 6 covers the SDN application plane. In addition to examining the general SDN application plane architecture, the chapter discusses six major application areas that can be supported by SDN and provides a number of examples of SDN applications.

- **Virtualization:** Devoted to a broad and thorough presentation of network functions virtualization (NFV) concepts, technology, and applications, as well as a discussion of network virtualization. Chapter 7 introduces the concept of virtual machine, and then looks at the use of virtual machine technology to develop NFV-based networking environments. Chapter 8 provides a detailed discussion of NFV functionality. Chapter 9 looks at traditional concepts of virtual networks, then at the more modern approach to network virtualization, and finally introduces the concept of software defined infrastructure.
- **Defining and Supporting User Needs:** Equally as significant as the emergence of the SDN and NFV is the evolution of quality of service (QoS) and quality of experience (QoE) to determine customer needs and network design responses to those needs. Chapter 10 provides an overview of QoS concepts and standards. Recently QoS has been augmented with the concept of QoE, which is particularly relevant to interactive video and multimedia network traffic. Chapter 11 provides an overview of QoE and discusses a number of practical aspects of implementing QoE mechanisms. Chapter 12 looks further into the network design implications of the combined use of QoS and QoE.
- **Modern Network Architecture: Clouds and Fog:** The two dominant modern network architectures are cloud computing and the Internet of things (IoT), sometimes referred to as fog computing. The technologies and applications discussed in the preceding parts all provide a foundation for cloud computing and IoT. Chapter 13 is a survey of cloud computing. The chapter begins with a definition of basic concepts, and then covers cloud services, deployment models, and architecture. The chapter then discusses the relationship between cloud computing and SDN and NFV. Chapter 14 introduces IoT and provides a detailed look at the key components of IoT-enabled devices. Chapter 15 looks at several model IoT architectures and then describes three example IoT implementations.
- **Related Topics:** Discusses two additional topics that, although important, do not conveniently fit into the other Parts. Chapter 16 provides an analysis of security issues that have emerged with the evolution of modern networking. Separate sections deal with SDN, NFV, cloud, and IoT security, respectively. Chapter 17 discusses career-related issues, including the changing role of various network-related jobs, new skill requirements, and how the reader can continue his or her education to prepare for a career in modern networking.

Supporting Websites

I maintain a companion website at WilliamStallings.com/Network that includes a list of relevant links organized by chapter and an errata sheet for the book.

Companion website

I also maintain the Computer Science Student Resource Site, at ComputerScienceStudent.com. The purpose of this site is to provide documents, information, and links for computer science students and professionals. Links and documents are organized into seven categories:

Computer Science Student Resource Site

- **Math:** Includes a basic math refresher, a queuing analysis primer, a number system primer, and links to numerous math sites.
- **How-to:** Advice and guidance for solving homework problems, writing technical reports, and preparing technical presentations.
- **Research resources:** Links to important collections of papers, technical reports, and bibliographies.
- **Other useful:** A variety of other useful documents and links.
- **Computer science careers:** Useful links and documents for those considering a career in computer science.
- **Writing help:** Help in becoming a clearer, more effective writer.
- **Miscellaneous topics and humor:** You have to take your mind off your work once in a while.

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Chapter 3

SDN: Background and Motivation

The requirements for a future all-digital-data distributed network which provides common user service for a wide range of users having different requirements is considered. The use of a standard format message block permits building relatively simple switching mechanisms using an adaptive store-and-forward routing policy to handle all forms of digital data including "real-time" voice. This network rapidly responds to changes in network status.

—On Distributed Communications: Introduction to Distributed Communications Networks, Rand Report RM-3420-PR, Paul Baran, August 1964

Chapter Objectives

After studying this chapter, you should be able to

- Make a presentation justifying the position that traditional network architectures are inadequate for modern networking needs.
- List and explain the key requirements for an SDN architecture.
- Present an overview of an SDN architecture, to include explaining the significance of northbound and southbound APIs.
- Summarize the work being done on SDN and NFV standardization by various organizations.

This chapter begins the discussion of software-defined networks (SDNs) by providing some background and motivation for the SDN approach.

3.1 Evolving Network Requirements

A number of trends are driving network providers and users to reevaluate traditional approaches to network architecture. These trends can be grouped under the categories of demand, supply, and traffic patterns.

Demand Is Increasing

As was described in Chapter 2, "Requirements and Technology," a number of trends are increasing the load on enterprise networks, the Internet, and other internets. Of particular note are the following:

- **Cloud computing:** There has been a dramatic shift by enterprises to both public and private cloud services.
- **Big data:** The processing of huge data sets requires massive parallel processing on thousands of servers, all of which require a degree of interconnection to each other. Therefore, there is a large and constantly growing demand for network capacity within the data canter.
- **Mobile traffic:** Employees are increasingly accessing enterprise network resources via mobile personal devices, such as smartphones, tablets, and notebooks. These devices support sophisticated apps that can consume and generate image and video traffic, placing new burdens on the enterprise network.
- **The Internet of Things (IoT):** Most "things" in the IoT generate modest traffic, although there are exceptions, such as surveillance video cameras. But the sheer number of such devices for some enterprises results in a significant load on the enterprise network.

Supply Is Increasing

As the demand on networks is rising, so is the capacity of network technologies to absorb rising loads. In terms of transmission technology, Chapter 1, "Elements of Modern Networking," established that the key enterprise wired and wireless network technologies, Ethernet and Wi-Fi respectively, are well into the gigabits per second (Gbps) range. Similarly, 4G and 5G cellular networks provide greater capacity for mobile devices from remote employees who access the enterprise network via cellular networks rather than Wi-Fi.

The increase in the capacity of the network transmission technologies has been matched by an increase in the performance of network devices, such as LAN switches, routers, firewalls, intrusion detection system/intrusion prevention systems (IDS/IPS),

and network monitoring and management systems. Year by year, these devices have larger, faster memories, enabling greater buffer capacity and faster buffer access, as well as faster processor speeds.

Traffic Patterns Are More Complex

If it were simply a matter of supply and demand, it would appear that today's networks should be able to cope with today's data traffic. But as traffic patterns have changed and become more complex, traditional enterprise network architectures are increasingly ill suited to the demand.

Until recently, and still common today, the typical enterprise network architecture consisted of a local or campus-wide tree structure of Ethernet switches with routers connecting large Ethernet LANs and connecting to the Internet and WAN facilities. This architecture is well suited to the client/server computing model that was at one time dominant in the enterprise environment. With this model, interaction, and therefore traffic, was mostly between one client and one server. In such an environment, networks could be laid out and configured with relatively static client and server locations and relatively predictable traffic volumes between clients and servers.

A number of developments have resulted in far more dynamic and complex traffic patterns within the enterprise data center, local and regional enterprise networks, and carrier networks. These include the following:

- Client/server applications typically access multiple databases and servers that must communicate with each other, generating "horizontal" traffic between servers as well as "vertical" traffic between servers and clients.
- Network convergence of voice, data, and video traffic creates unpredictable traffic patterns, often of large multimedia data transfers.
- Unified communications (UC) strategies involve heavy use of applications that trigger access to multiple servers.
- The heavy use of mobile devices, including personal bring your own device (BYOD) policies, results in user access to corporate content and applications from any device anywhere any time. As illustrated previously in Figure 2.6 in Chapter 2, this mobile traffic is becoming an increasingly significant fraction of enterprise network traffic.
- The widespread use of public clouds has shifted a significant amount of what previously had been local traffic onto WANs for many enterprises, resulting in increased and often very unpredictable loads on enterprise routers.
- The now-common practice of application and database server virtualization has significantly increased the number of hosts requiring high-volume network access and results in every-changing physical location of server resources.

Traditional Network Architectures are Inadequate

Even with the greater capacity of transmission schemes and the greater performance of network devices, traditional network architectures are increasingly inadequate in the face of the growing complexity, variability, and high volume of the imposed load. In addition, as quality of service (QoS) and quality of experience (QoE) requirements imposed on the network are expanded as a result of the variety of applications, the traffic load must be handled in an increasingly sophisticated and agile fashion.

The traditional internetworking approach is based on the **TCP/IP protocol architecture**. Three noteworthy characteristics of this approach are as follows:

- Two-level end system addressing
- Routing based on destination
- Distributed, autonomous control

TCP/IP protocol architecture

The protocol architecture built around the TCP and IP protocols, consisting of five layers: physical, data link, network/Internet (usually IP), transport (usually TCP or UDP), and application.

Let's look at each of these characteristics in turn.

The traditional architecture relies heavily on the network interface identity. At the physical layer of the TCP/IP model, devices attached to networks are identified by hardware-based identifiers, such as Ethernet MAC addresses. At the internetworking level, including both the Internet and private internets, the architecture is a network of networks. Each attached device has a physical layer identifier recognized within its immediate network and a logical network identifier, its IP address, which provides global visibility.

packet

A unit of data sent across a network. A packet is a group of bits that includes data plus protocol control information. The term generally applies to protocol data units at the network layer.

The design of TCP/IP uses this addressing scheme to support the networking of autonomous networks, with distributed control. This architecture provides a high level of resilience and scales well in terms of adding new networks. Using IP and distributed routing protocols, routes can be discovered and used throughout an internet. Using transport-level protocols such as TCP, distributed and decentralized algorithms can be implemented to respond to congestion.

Traditionally, routing was based on each packet's destination address. In this **datagram** approach, successive packets between a source and destination may follow different routes through the internet, as routers constantly seek to find the minimum-delay path for each individual **packet**. More recently, to satisfy QoS requirements, packets are often treated in terms of **flows** of packets. Packets associated with a given flow have defined QoS characteristics, which affect the routing for the entire flow.

packet switching

A method of transmitting messages through a communications network, in which long messages are subdivided into short packets. Each packet is passed from source to destination through intermediate nodes. At each node, the entire message is received, stored briefly, and then forwarded to the next node.

However, this distributed, autonomous approach developed when networks were predominantly static and end systems predominantly of fixed location. Based on these characteristics, the Open Networking Foundation (ONF) cites four general limitations of traditional network architectures [ONF12]:

Datagram

A packet that is treated independently of other packets for packet switching. A datagram carries information sufficient for routing from the source to the destination without the necessity of establishing a logical connection between the endpoints.

flow

A sequence of packets between a source and destination that are recognized by the network as related and are treated in a uniform fashion.

- **Static, complex architecture:** To respond for demands such as differing levels of QoS, high and fluctuating traffic volumes, and security requirements, networking technology has grown more complex and difficult to manage. This has resulted in a number of independently defined protocols each of which addresses a portion of networking requirements. An example of the difficulty this presents is when devices are added or moved. The network management staff must use device-level management tools to make changes to configuration parameters in multiple switches, routers, firewalls, web authentication portals, and so on. The updates include changes to access control lists (ACLs), virtual LAN settings, QoS settings in numerous devices, and other protocol-related adjustments. Another example is the adjustment of QoS parameters to meet changing user requirements and traffic patterns. Manual procedures must be used to configure each vendor's equipment on a per-application and even per-session basis.
- **Inconsistent policies:** To implement a network-wide security policy, staff may have to make configuration changes to thousands of devices and mechanisms. In a large network, when a new virtual machine is activated, it can take hours or even days to reconfigure ACLs across the entire network.
- **Inability to scale:** Demands on networks are growing rapidly, both in volume and variety. Adding more switches and transmission capacity, involving multiple vendor equipment, is difficult because of the complex, static nature of the network. One strategy enterprises have used is to oversubscribe network links based on predicted traffic patterns. But with the increased use of virtualization and the increasing variety of multimedia applications, traffic patterns are unpredictable.
- **Vendor dependence:** Given the nature of today's traffic demands on networks, enterprises and carriers need to deploy new capabilities and services rapidly in response to changing business needs and user demands. A lack of open interfaces for network functions leaves the enterprises limited by the relatively slow product cycles of vendor equipment.

3.2 The SDN Approach

This section provides an overview of SDN and shows how it is designed to meet evolving network requirements.

Requirements

Based on the narrative of Section 3.1, we are now in a position to detail the principal requirements for a modern networking approach. The Open Data Center Alliance (ODCA) provides a useful, concise list of requirements, which include the following [ODCA14]:

- **Adaptability:** Networks must adjust and respond dynamically, based on application needs, business policy, and network conditions.
- **Automation:** Policy changes must be automatically propagated so that manual work and errors can be reduced.
- **Maintainability**. Introduction of new features and capabilities (software upgrades, patches) must be seamless with minimal disruption of operations.
- **Model management:** Network management software must allow management of the network at a model level, rather than implementing conceptual changes by reconfiguring individual network elements.
- **Mobility:** Control functionality must accommodate mobility, including mobile user devices and virtual servers.
- **Integrated security:** Network applications must integrate seamless security as a core service instead of as an add-on solution.
- **On-demand scaling:** Implementations must have the ability to scale up or scale down the network and its services to support on-demand requests.

SDN Architecture

An analogy can be drawn between the way in which computing evolved from closed, vertically integrated, proprietary systems into an open approach to computing and the evolution coming with SDN (see Figure 3.1). In the early decades of computing, vendors such as IBM and DEC provided a fully integrated product, with a proprietary processor hardware, unique assembly language, unique operating system (OS), and the bulk if not all of the application software. In this environment, customers, especially large customers, tended to be locked in to one vendor, dependent primarily on the applications offered by that vendor. Migration to another vendor's hardware platform resulted in major upheaval at the application level.

Today, the computing environment is characterized by extreme openness and great customer flexibility. The bulk of computing hardware consists of x86 and x86-compatible processors for standalone systems and ARM processors for embedded systems. This makes it easy to port operating systems implemented in C, C++, Java, and the like. Even proprietary hardware architectures, such as IBM's zEnterprise line, provide standardized compilers and programming environments and so can easily run open sources operating systems such as Linux. Therefore, applications written for Linux or other open operating systems can easily be moved from one vendor platform to another. Even proprietary systems such as Windows and Mac OS provide programming environments to make porting of applications an easy matter. It also enables the development of virtual machines that can be moved from one server to another across hardware platforms and operating systems.

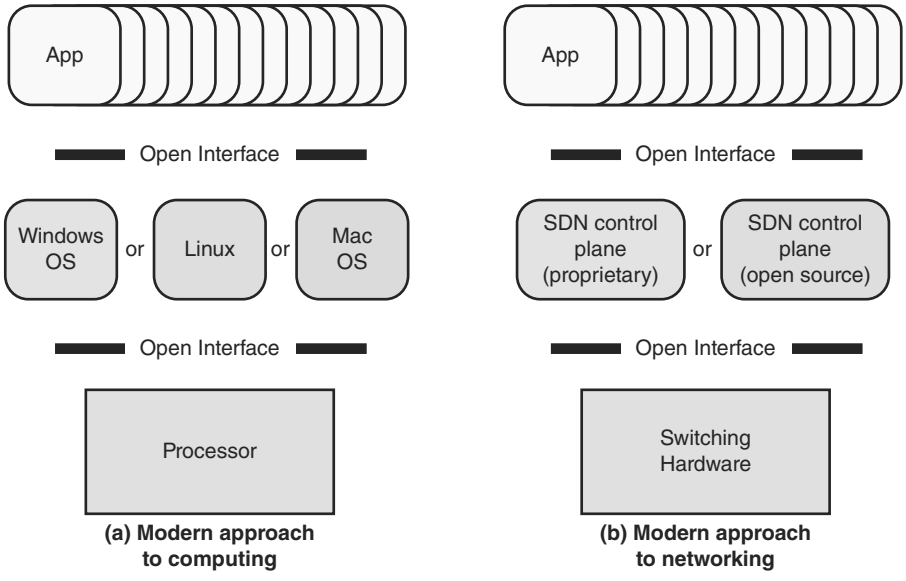

FIGURE 3.1 The Modern Approach to Computing and Networking

The networking environment today faces some of the same limitations faced in the pre-open era of computing. Here the issue is not developing applications that can run on multiple platforms. Rather, the difficulty is the lack of integration between applications and network infrastructure. As demonstrated in the preceding section, traditional network architectures are inadequate to meet the demands of the growing volume and variety of traffic.

The central concept behind SDN is to enable developers and network managers to have the same type of control over network equipment that they have had over x86 servers. As discussed in Section 2.6 in Chapter 2, the SDN approach splits the switching function between a data plane and a control plane that are on separate devices (see Figure 3.2). The data plane is simply responsible for forwarding packets, whereas the control plane provides the "intelligence" in designing routes, setting priority and routing policy parameters to meet QoS and QoE requirements and to cope with the shifting traffic patterns. Open interfaces are defined so that the switching hardware presents a uniform interface regardless of the details of internal implementation. Similarly, open interfaces are defined to enable networking applications to communicate with the SDN controllers.

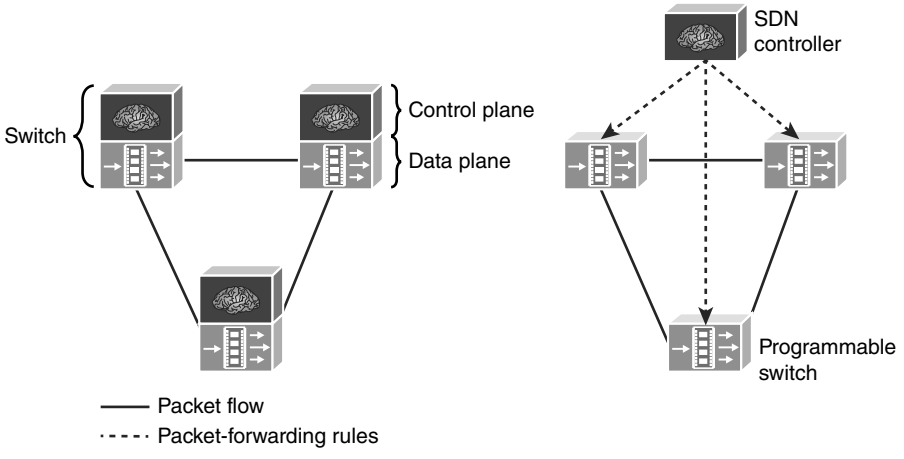

FIGURE 3.2 Control and Data Planes

See Figure 2.15, Software Defined Networking

Figure 3.3 elaborates on the structure shown in Figure 2.15, showing more detail of the SDN approach. The data plane consists of physical switches and virtual switches. In both cases, the switches are responsible for forwarding packets. The internal implementation of buffers, priority parameters, and other data structures related to forwarding can be vendor dependent. However, each switch must implement a model, or abstraction, of packet forwarding that is uniform and open to the SDN controllers. This model is defined in terms of an open **application programming interface (API)** between the control plane and the data plane (southbound API). The most prominent example of such an open API is OpenFlow, discussed in Chapter 4, "SDN Data Plane and OpenFlow." As Chapter 4 explains, the OpenFlow specification defines both a protocol between the control and data planes and an API by which the control plane can invoke the OpenFlow protocol.

application programming interface (API)

A language and message format used by an application program to communicate with the operating system or some other control program such as a database management system (DBMS) or communications protocol. APIs are implemented by writing function calls in the program, which provide the linkage to the required subroutine for execution. An open or standardized API can ensure the portability of the application code and the vendor independence of the called service.

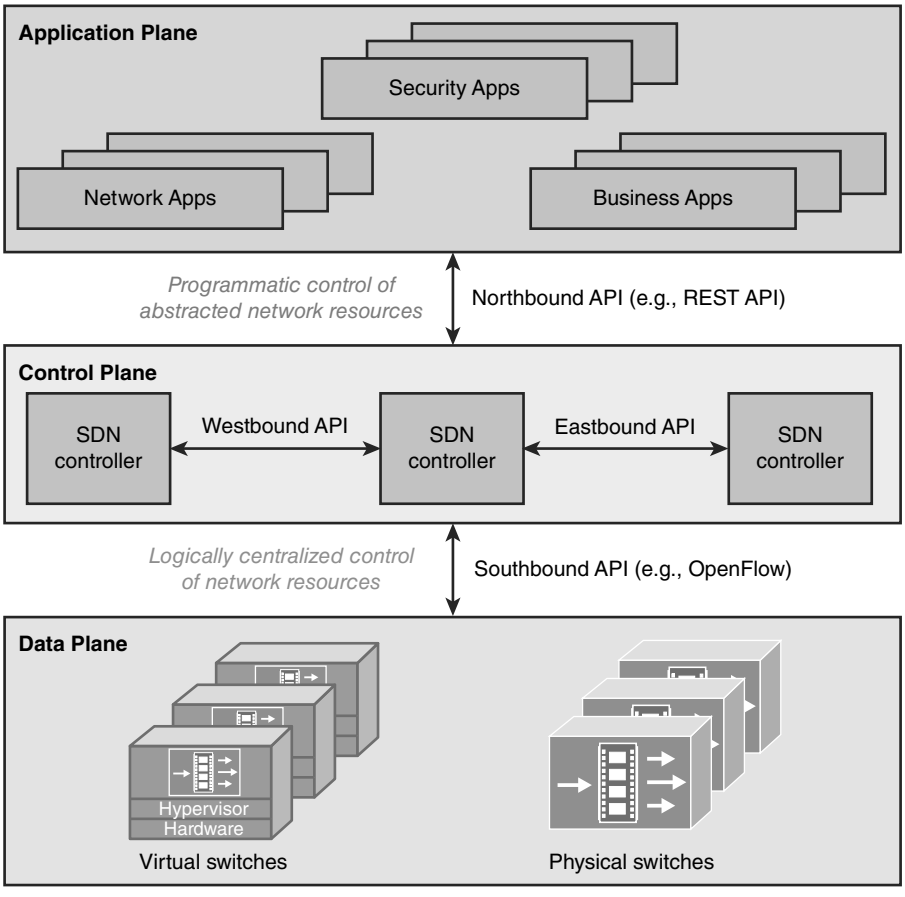

FIGURE 3.3 Software-Defined Architecture

→ *See Chapter 5, "SDN Control Plane"*

SDN controllers can be implemented directly on a server or on a virtual server. OpenFlow or some other open API is used to control the switches in the data plane. In addition, controllers use information about capacity and demand obtained from the networking equipment through which the traffic flows. SDN controllers also expose northbound APIs, which allow developers and network managers to deploy a wide range of off-the-shelf and custom-built network applications, many of which were not feasible before the advent of SDN. As yet there is no standardized northbound API nor a consensus on an open northbound API. A number of vendors offer a REpresentational State Transfer (REST)-based API to provide a programmable interface to their SDN controller.

Also envisioned but not yet defined are horizontal APIs (east/westbound), which would enable communication and cooperation among groups or federations of controllers to synchronize state for high availability.

At the application plane are a variety of applications that interact with SDN controllers. SDN applications are programs that may use an abstract view of the network for their decision-making goals. These applications convey their network requirements and desired network behavior to the SDN controller via a northbound API. Examples of applications are energy-efficient networking, security monitoring, access control, and network management.

Characteristics of Software-Defined Networking

Putting it all together, the key characteristics of SDN are as follows:

- The control plane is separated from the data plane. Data plane devices become simple packet-forwarding devices (refer back to Figure 3.2).
- The control plane is implemented in a centralized controller or set of coordinated centralized controllers. The SDN controller has a centralized view of the network or networks under its control. The controller is portable software that can run on commodity servers and is capable of programming the forwarding devices based on a centralized view of the network.
- Open interfaces are defined between the devices in the control plane (controllers) and those in the data plane.
- The network is programmable by applications running on top of the SDN controllers. The SDN controllers present an abstract view of network resources to the applications.

3.3 SDN- and NFV-Related Standards

Unlike some technology areas, such as Wi-Fi, there is no single standards body responsible for developing open **standards** for SDN and NFV. Rather, there is a large and evolving collection of standards-developing organizations (SDOs), industrial consortia, and open development initiatives involved in creating standards and guidelines for SDN and NFV. Table 3.1 lists the main SDOs and other organizations involved in the effort and the main outcomes so far produced. This section covers some of the most prominent efforts.

standards

Documents that provide requirements, specifications, guidelines, or characteristics that can be used consistently to ensure that materials, products, processes, and services are fit for their purpose. Standards are established by consensus among those participating in a standards-making organization and are approved by a generally recognized body.

open standard

A standard that is: developed on the basis of an open decision-making procedure available to all interested parties, is available for implementation to all on a royalty-free basis, and is intended to promote interoperability among products from multiple vendors.

TABLE 3.1 SDN and NFV Open Standards Activities

Organization	Mission	SDN- and NFV-Related Effort
Open Networking Foundation (ONF)	An industry consortium dedicated to the promotion and adoption of SDN through open standard development.	OpenFlow
Internet Engineering Task Force (IETF)	The Internet's technical standards body. Produces RFCs and Internet standards.	Interface to routing systems (I2RS) Service function chaining
European Telecommunications Standards Institute (ETSI)	An EU-sponsored standards organization that produces globally applicable standards for information and communications technologies.	NFV architecture
OpenDaylight	A collaborative project under the auspices of the Linux Foundation.	OpenDaylight
International Telecommunication Union—Telecommunication Standardization Sector (ITU-T)	United Nations agency that produces Recommendations with a view to standardizing telecommunications on a worldwide basis.	SDN functional requirements and architecture
Internet Research Task Force (IRTF) Software Defined Networking Research Group (SDNRG)	Research group within IRTF. Produces SDN-related RFCs.	SDN architecture
Broadband Forum (BBF)	Industry consortium developing broadband packet networking specifications.	Requirements and framework for SDN in telecommunications broadband networks
Metro Ethernet Forum (MEF)	Industry consortium that promotes the use of Ethernet for metropolitan and wide-area applications.	Defining APIs for service orchestration over SDN and NFV
IEEE 802	An IEEE committee responsible for developing standards for LANs.	Standardize SDN capabilities on access networks.
Optical Internetworking Forum (OIF)	Industry consortium promoting development and deployment of interoperable networking solutions and services for optical networking products.	Requirements on transport networks in SDN architectures

Organization	Mission	SDN- and NFV-Related Effort
Open Data Center Alliance (ODCA)	Consortium of leading IT organizations developing interoperable solutions and services for cloud computing.	SDN usage model
Alliance for Telecommunications Industry Solutions (ATIS)	A standards organization that develops standards for the unified communications (UC) industry.	Operational opportunities and challenges of SDN/NFV programmable infrastructure
Open Platform for NFV (OPNFV)	An open source project focused on accelerating the evolution of NFV.	NFV infrastructure

Standards-Developing Organizations

The Internet Society, ITU-T, and ETSI are all making key contributions to the standardization of SDN and NFV.

Internet Society

A number of **standards-developing organizations (SDOs)** are looking at various aspects of SDN. Perhaps the most active are two groups within the Internet Society (ISOC): IETF and IRTF. ISOC is the coordinating committee for Internet design, engineering, and management. Areas covered include the operation of the Internet itself and the standardization of protocols used by end systems on the Internet for interoperability. Various organizations under the ISOC are responsible for the actual work of standards development and publication.

The Internet Engineering Task Force (IETF) has working groups developing SDN-related specifications in the following areas:

- **Interface to routing systems (I2RS):** Develop capabilities to interact with routers and routing protocols to apply routing policies.
- **Service function chaining**: Develop an architecture and capabilities for controllers to direct subsets of traffic across the network in such a way that each virtual service platform sees only the traffic it must work with.

The Internet Research Task Force (IRTF) has published *Software-Defined Networking (SDN): Layers and Architecture Terminology* (RFC 7426, January 2015). The document provides a concise reference that reflects current approaches regarding the SDN layer architecture. The **Request For Comments (RFC)** also provides a useful discussion of the southbound API (Figure 3.3) and describes some specific APIs, such as for I2RS.

standards-developing organization (SDO)

An official national, regional, or international standards body that develops standards and coordinates the standard activities of a specific country, region or the world. Some SDOs facilitate the development of standards through support of technical committee activities, and some may be directly involved in standards development.

Request For Comments (RFC)

A document in the archival series that is the official channel for publications of the Internet Society, including IETF and IRTF publications. An RFC may be informational, best practice, draft standard, or an official Internet standard.

IRTF also sponsors the Software Defined Networking Research Group (SDNRG). This group investigates SDN from various perspectives with the goal of identifying the approaches that can be defined, deployed, and used in the near term and identifying future research challenges.

ITU-T

The International Telecommunication Union—Telecommunication Standardization Sector (ITU-T) is a UN agency that issues standards, called recommendations, in the telecommunications area. So far, their only published contribution to SDN is Recommendation Y.3300 (*Framework of Software-Defined Networking*, June 2014). The document addresses definitions, objectives, high-level capabilities, requirements, and high-level architecture of SDN. It provides a valuable framework for standards development.

ITU-T has established a Joint Coordination Activity on Software-Defined Networking (JCA-SDN) and begun work on developing SDN-related standards.

Four ITU-T study groups (SGs) are involved in SDN-related activities:

- **SG 13 (Future networks, including cloud computing, mobile, and next-generation networks):** This is the lead study group of SDN in ITU-T and developed Y.3300. This group is studying SDN and virtualization aspects for next-generation networks (NGNs).
- **SG 11 (Signaling requirements, protocols, and test specifications):** This group is studying the framework for SDN signaling and how to apply SDN technologies for IPv6.
- **SG 15 (Transport, access, and home):** This group looks at optical transport networks, access networks, and home networks. The group is investigating transport aspects of SDN, aligned with the Open Network Foundation's SDN architecture.
- **SG 16 (Multimedia):** This group is evaluating OpenFlow as a protocol to control multimedia packet flows, and is studying virtual content delivery networks.

European Telecommunications Standards Institute

ETSI is recognized by the European Union as a European Standards Organization. However, this not-for-profit SDO has member organizations worldwide and its standards have international impact.

ETSI has taken the lead role in defining standards for NFV. ETSI's Network Functions Virtualisation (NFV) Industry Specification Group (ISG) began work in January 2013 and produced a first set of specifications in January 2015. The 11 specifications

include an NFV's architecture, infrastructure, service quality metrics, management and orchestration, resiliency requirements, and security guidance.

Industry Consortia

Consortia for open standards began to appear in the late 1980s. There was a growing feeling within private-sector multinational companies that the SDOs acted too slowly to provide useful standards in the fast-paced world of technology. Recently, a number of consortia have become involved in the development of SDN and NFV standards. We mention here three of the most significant efforts.

→ *See Chapter 4, "SDN Data Plane and OpenFlow"*

By far the most important **consortium** involved in SDN standardization is the Open Networking Foundation (ONF). ONF is an industry consortium dedicated to the promotion and adoption of SDN through open standards development. Its most important contribution to date is the OpenFlow protocol and API. The OpenFlow protocol is the first standard interface specifically designed for SDN and is already being deployed in a variety of networks and networking products, both hardware based and software based. The standard enables networks to evolve by giving logically centralized control software the power to modify the behavior of network devices through a well-defined "forwarding instruction set." Chapter 4 is devoted to this protocol.

consortium
A group of independent organizations joined by common interests. In the area of standards development, a consortium typically consists of individual corporations and trade groups concerned with a specific area of technology.

The Open Data Center Alliance (ODCA) is a consortium of leading global IT organizations dedicated to accelerating adoption of interoperable solutions and services for cloud computing. Through the development of usage models for SDN and NFV, ODCA is defining requirements for SDN and NFV cloud deployment.

The Alliance for Telecommunications Industry Solutions (ATIS) is a membership organization that provides the tools necessary for the industry to identify standards, guidelines, and operating procedures that make the interoperability of existing and emerging telecommunications products and services possible. Although ATIS is accredited by ANSI, it is best viewed as a consortium rather than an SDO. So far, ATIS has issued a document that identifies operational issues and opportunities associated with increasing programmability of the infrastructure using SDN and NFV.

Open Development Initiatives

There are a number of other organizations that are not specifically created by industry members and are not official bodies such as SDOs. Generally, these organizations are user created and driven and have a particular focus, always with the goal of developing open standards or open source software. A number of such groups have become

active in SDN and NFV standardization. This section lists three of the most significant efforts.

OpenDaylight

→ *See Section 5.3, "OpenDaylight"*

OpenDaylight is an open source software activity under the auspices of the Linux foundation. Its member companies provide resources to develop an SDN controller for a wide range of applications. Although the core membership consists of companies, individual developers and users can also participate, so OpenDaylight is more in the nature of an open development initiative than a consortium. ODL also supports network programmability via southbound protocols, a bunch of programmable network services, a collection of northbound APIs, and a set of applications.

OpenDaylight is composed of about 30 projects, and releases their outputs in simultaneous manner. After its first release, Hydrogen, in February 2014, it successfully delivered the second one, Helium, at the end of September 2014.

Open Platform for NFV

→ *See Section 7.4, "NFV Benefits and Requirements"*

Open Platform for NFV is an open source project dedicated to acceleration the adoption of standardized NFV elements. OPNFV will establish a carrier-grade, integrated, open source reference platform that industry peers will build together to advance the evolution of NFV and to ensure consistency, performance, and interoperability among multiple open source components. Because multiple open source NFV building blocks already exist, OPNFV will work with upstream projects to coordinate continuous integration and testing while filling development gaps.

OpenStack

OpenStack is an open source software project that aims to produce an open source cloud operating system. It provides multitenant Infrastructure as a Service (IaaS), and aims to meets the needs of public and private clouds regardless of size, by being simple to implement and massively scalable. SDN technology is expected to contribute to its networking part, and to make the cloud operating system more efficient, flexible, and reliable.

OpenStack is composed of a number of projects. One of them, Neutron, is dedicated for networking. It provides Network as a Service (NaaS) to other OpenStack services. Almost all SDN controllers have provided plug-ins for Neutron, and through them services on OpenStack and other OpenStack services can build rich networking topologies and can configure advanced network policies in the cloud.

3.4 Key Terms

After completing this chapter, you should be able to define the following terms.

application programming interface (API)
consortium
datagram
flow
IEEE 802
northbound API
open standard
packet switching
REpresentational State Transfer (REST)
Request For Comments (RFC)
service function chaining
southbound API
standard
standards-developing organization (SDO)
TCP/IP protocol architecture

3.5 References

ODCA14: Open Data Center Alliance. *Open Data Center Alliance Master Usage Model: Software-Defined Networking Rev. 2.0*. White Paper. 2014.

ONF12: Open Networking Foundation. *Software-Defined Networking: The New Norm for Networks.* ONF White Paper, April 13, 2012.

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