CHAPTER

PLAYERS IN THE SDN ECOSYSTEM

11

A technological shift as radical and ambitious as SDN does not happen without many players contributing to its evolution. Beyond the luminaries behind the early concepts of SDN there are many organizations that continue to influence the direction in which SDN is headed and its rate of growth. Their impact is sometimes positive and at other times contrary to the growth of SDN, but are in any case influential in the evolution of SDN. We classify the various organizations that have had the most influence on SDN into the following categories:

- Academic Researchers
- Industry Research Labs
- Network Equipment Manufacturers
- Software Vendors
- Merchant Silicon Vendors
- Original Device Manufacturers
- Enterprises and Service Providers
- Standards Bodies
- Industry and Open Source Alliances

Fig. 11.1 depicts these major groupings of SDN players and the synergies and conflicts that exist between them. We also show three super-categories in the figure. Academic and industry-based basic research, standards bodies and industry alliances, and the *white-box* ecosystem make up these super-categories. In the context of this book, a white-box switch is a hardware platform that is purpose-built to easily incorporate a *Network Operating System* (NOS) from another vendor or from open source. In the context of this book, an NOS is normally OpenFlow device software that would come in the form of an OpenFlow implementation such as Switch Light or OVS. In this chapter we will discuss each of these categories, how they have contributed to the evolution of SDN, and the various forces that draw them together or place them into conflict.

11.1 ACADEMIC RESEARCH INSTITUTIONS

Universities worldwide have engaged in research related to SDN. While many academic institutions have contributed to the advancement of SDN, we mention here three institutions of particular interest. They are Stanford University, UC Berkeley, and Indiana University. Stanford and UC Berkeley were at the forefront of SDN since its very inception and have employed an impressive number of the luminaries that created this new model of networking.

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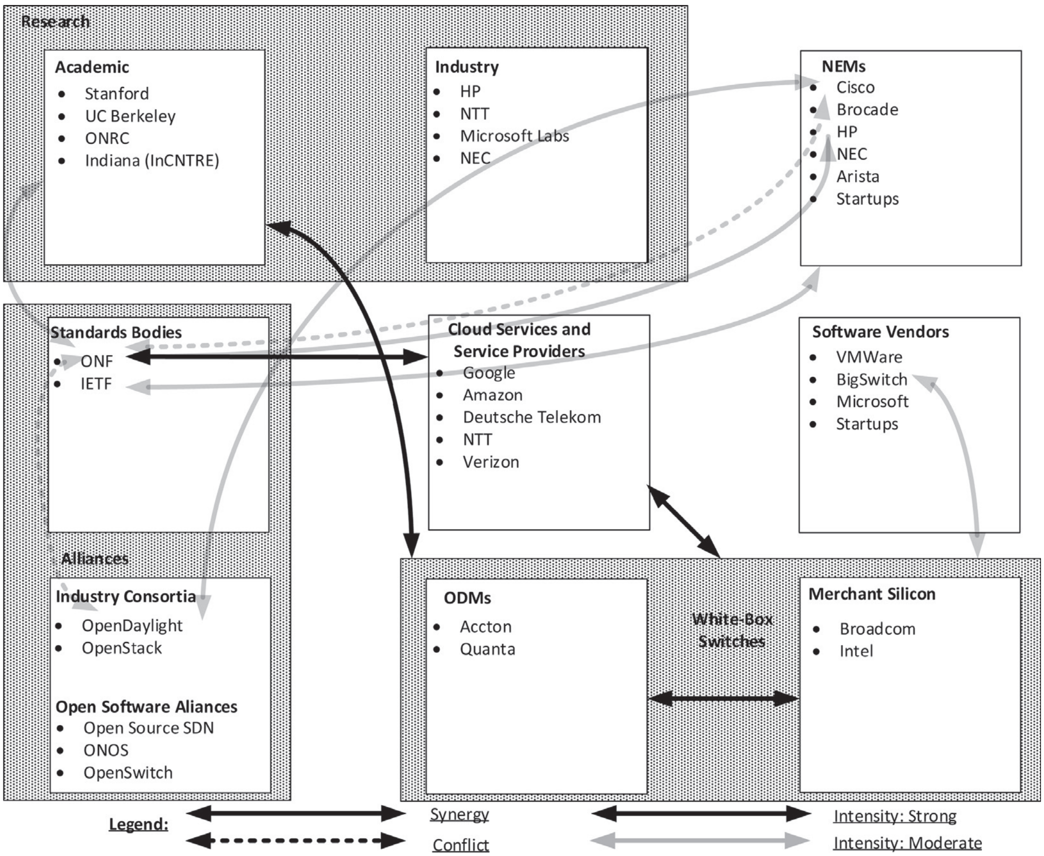

FIG. 11.1

SDN players ecosystem.

As we saw in Section 3.2.6, events at Stanford University led directly to the creation of the *Clean Slate* [1] program, including forwarding and control plane separation and, notably, the OpenFlow protocol. The *Open Networking Research Center* (ONRC) began as a joint project by Stanford and UC Berkeley [2], receiving funding from a number of major vendors such as Cisco, Intel, Google, VMware, and others. Its stated intention is to *open up the Internet infrastructure for innovations*. The ONRC has produced a number of research projects [3]. There is an affiliated organization called ON.Lab which seeks to develop, deploy, and support various SDN and OpenFlow-related tools and platforms. The ONRC is more research oriented while the ON.Lab is more focused on the practical application of SDN.

Indiana University has been instrumental in promoting SDN and OpenFlow, with a number of research projects and implementations, including the *Indiana Center for Network Translational Research and Education* (InCNTRE) [4]. Their goal is to *advance development*, *increase knowledge*, and *encourage adoption of OpenFlow and other standards-based SDN technologies*. One of the most notable activities at InCNTRE is a plugfest hosted by the *Open Networking Foundation* (ONF), where vendors bring their networking devices and controllers for interoperability testing. InCNTRE is the first certified lab selected by ONF for their conformance testing program [5].

In addition to the research institutions themselves, numerous academic conferences provide a fertile environment for the discussion of the future of SDN. These include *SIGCOMM*, *HotSDN*, *The Symposium on SDN Research* (SOSR), and *CoNEXT*, among others.

DISCUSSION QUESTION

Fig. 11.1 shows potential conflict between standards bodies and NEMs. Explain what the source of this conflict might be?

11.1.1 KEY CONTRIBUTORS TO SDN FROM ACADEMIA

A significant number of SDN pioneers have worked or studied at Stanford and UC Berkeley, some of whom we list as follows:

- Nick McKeown is currently a professor of Electrical Engineering and Computer Science at Stanford. He has established multiple technology companies which have been acquired by larger companies in the high-tech industry. He is credited with helping to ignite the SDN movement along with Martin Casado and Scott Shenker.
- Martin Casado is a member of the High Performance Networking research group at Stanford University. He co-founded Nicira with Nick McKeown and Scott Shenker and is currently working with the Andreessen Horowitz venture capital firm. He was initially one of the creators of OpenFlow through the Ethane project [6].
- Scott Shenker is a professor in the School of Electrical Engineering and Computer Science at UC Berkeley and was involved with Nick McKeown and Martin Casado in the creation of Nicira.
- Guru Parulkar is a consulting professor at Stanford as well as having been Executive Director of the Clean Slate program at that university. He is also Executive Director of the ONRC and ON.Lab. He is a strong advocate of Open SDN and a vocal opponent of *SDN washing* [7]. SDN washing means the use of the term SDN to refer to related technologies other than Open SDN, such as SDN via APIs and SDN via Hypervisor-based Overlays.
- Guido Appenzeller is co-founder of Big Switch Networks and is another participant in Stanford's Clean Slate program. In his role at Big Switch he is one of the strongest advocates for the Open SDN approach to reinventing networks.
- David Erickson and Rob Sherwood are the authors of many of the modules for the Beacon SDN controller [8]. As most of the current open source SDN controllers were forked from that original Beacon source code, they have had significant influence on the design of contemporary Open SDN controllers. Floodlight, for example, was derived from Beacon.

DISCUSSION QUESTION

Why do you think that Fig. 11.1 shows a high level of synergy between SDN academic researchers and the white-box ecosystem?

11.2 INDUSTRY RESEARCH LABS

Quite often major enterprises and vendors support their own labs which are performing basic research. We distinguish such pure research from that which is directed toward specific product development. These corporations often participate in research organizations and conferences and contribute papers based on their findings. For example, some research labs that have presented papers on SDN at SIGCOMM conferences are listed as follows:

- Telekom Innovation Laboratories (research arm of Deutsche Telekom)
- NTT Innovation Institute
- Microsoft Research
- Hewlett-Packard (HP) Laboratories[1]
- Fujitsu Laboratories Ltd.
- IBM Research
- NEC Labs

These companies contribute to the furthering of Software Defined Networking through research into topics such as scalability, deployment alternatives, ASIC development, and many other topics central to SDN.

11.3 NETWORK EQUIPMENT MANUFACTURERS

A number of networking vendors were quick to join the SDN movement, some of them contributing OpenFlow-enabled devices to researchers for testing even before the first official OpenFlow standard document was published. Others have provided funding for SDN-related standards organizations, industry alliances, or research institutions. Some have made small acquisitions to gain access to SDN technology. While some have begun to support Open SDN, others promote an SDN via APIs or an SDN via Overlays strategy.

Virtually every NEM has SDN as part of its story today. This is a marketing necessity considering all the hype surrounding SDN, yet much of it constitutes the SDN washing described earlier in Section 11.1.1. It is not our intent in this chapter to document all of the vendors' SDN claims. We focus on specific NEMs that, either because of their size or their commitment to SDN, seem most likely to influence the future course of SDN, for better or worse. In Table 11.1 we list some of these SDN networking vendors and the products they offer in the areas of SDN device, SDN controller, and SDN application. The NEMs called out in the table are not the only ones to have brought SDN products to the market as of this writing, but we believe that they reflect the most significant contributions by NEMs thus far. We provide some brief background on the NEMs cited in Table 11.1.

Cisco was not involved with the early work on OpenFlow and began to support OpenFlow in its devices in 2012. Cisco is now heavily involved with SDN. While only a lukewarm supporter of the ONF, Cisco is the primary driving force behind the OpenDaylight (ODL) Project, focused on an open-source SDN controller which we discuss in Section 11.9.2. In addition to their open source efforts

[1]In Nov. 2015 HP split into two separate companies, Hewlett-Packard Enterprise (HPE) and HP Inc. As the networking business will stay with HPE, our remarks about HP regarding events after November 2015 actually pertain to HPE. We will not make that distinction elsewhere in the text, though, due to our readers' long familiarity with the name HP.

Table 11.1 SDN Commercial Products

Vendor	SDN Devices	SDN Controller	SDN Applications
Cisco	SDN via APIs OpenFlow: Nexus	COSC APIC-DC APIC-EM	WAE
Hewlett-Packard	OpenFlow: 3500, 5400, and 8200	VAN	Security (Sentinel)
Brocade	OpenFlow: NetIron CER, CES SDN via APIs	Brocade SDN Controller (Vyatta)	
VMware	OpenFlow: Open vSwitch (OVS)	NVP (NSX)	NVP (NSX)
Big Switch	OpenFlow: Indigo OpenFlow: Switch Light	Big Network Controller	Big Cloud Fabric Big Tap
IBM	OpenFlow: RackSwitch and Flex System	Programmable Network Controller	SDN VE DOVE
NEC	Programmable Flow 5240 and 5820	Programmable Flow Controller	Virtual Tenant Networks Firewall, others
Extreme	OpenFlow	ADARA	
Juniper	OpenFlow: MX, EX series	Contrail	
Alcatel-Lucent[a]	SDN via APIs	Nuage VSC	
Arista	OpenFlow: 7050 series SDN via APIs	VMware NVP Nuage VSC	

[a]*Alcatel-Lucent is now part of Nokia.*

in the ODL project, Cisco strongly promotes SDN via their proprietary APIs. They claim to support APIs and programmability to more of the networking stack than is available with only OpenFlow. We presented this architecture in detail in Section 7.2. With regard to commercial controllers, Cisco emphasizes their *Application Policy Infrastructure Controller* (APIC). They also offer the *Cisco Open SDN Controller* (COSC), which is their commercial version of the ODL controller. As the dominant NEM, Cisco will undoubtedly play a large part in shaping the role that SDN will assume in industry. As Cisco creates APIs, other vendors will pragmatically follow suit and provide the same or very similar APIs in order to sell into Cisco markets, creating de facto standards. This process is unfolding within the ODL project. Examples of this are the ODL BGP-LS/PCEP plugin described in Section 7.2 and the MD-SAL architecture discussed in Section 7.3.2.

Note that Cisco's acquisitions of *spin-in* Insieme, Cariden, Tail-f, and Embrane that we discuss in Chapter 14 is further evidence of their growing interest in SDN.

Brocade has been active for a number of years in providing OpenFlow-supporting networking devices to researchers. However, they also provide SDN via APIs support in their devices and have promoted their RESTful API SDN support in use cases with various customers. This dual-pronged approach allows Brocade to offer short-term transition plans to their customers by offering SDN APIs on their devices as a migration path, as well as supporting Open SDN as a longer-term strategy. Brocade is currently a major supporter of the ODL project. In Section 14.8.3 we will discuss Brocade's acquisition of Vyatta, another SDN-related startup.

NEC and IBM have partnered together from the early days of the OpenFlow project. Their OpenFlow switch and controller implementations have similar capabilities. Both vendors have been stalwart contributors to the OpenFlow research community of OpenFlow-enabled switches. Both vendors have created applications for their controllers, including virtualization applications which implement overlay technology. Both companies are committed to OpenFlow and support SDN via Overlays using OpenFlow as the southbound API from the controller. As founding members of ODL, IBM and NEC have ported their virtualization applications to run on that controller. NEC contributed a version of their own network virtualization application, called *Virtual Tenant Networks*. IBM contributed a version of their network virtualization application, *SDN Virtual Environments*, which is called *Distributed Overlay Virtual Ethernet* (DOVE) in the ODL environment (see Section 6.3.3).

Like NEC and IBM, Hewlett-Packard has contributed OpenFlow-supporting switches to the OpenFlow research community long before the first ratified version of OpenFlow was approved. HP continues to support OpenFlow in many switch product lines and claims to have shipped millions of OpenFlow-supporting switch ports in the past few years. Among NEMs, HP stands out for its unequivocal support of OpenFlow and enthusiastic participation in the ONF.

HP offers the commercial OpenFlow-based VAN SDN controller. At ONS 2013 HP presented a number of SDN applications using OpenFlow to implement security and traffic-prioritization features. HP currently offers the Sentinel SDN security application that we described in Section 9.3.3. Because of its large server business, HP is also heavily involved in OpenStack and, consequently, HP will likely provide some type of network virtualization support through that project.

In Table 11.1 we see several NEMs listed that we have not yet mentioned. Extreme Networks, a long-time NEM, is partnering with ADARA, a provider of infrastructure orchestration products for SDN and cloud computing [9]. Extreme hopes that this partnership will allow their customers to migrate their existing networks to SDN without wholesale hardware upgrades. Alcatel-Lucent provides SDN via APIs in their networking devices. Juniper is headed toward a strategy aligned with SDN via APIs and has also acquired the startup Contrail. The Contrail controller provides network virtualization technology via overlays. Arista is very vocal in SDN forums and ships commercial SDN products. While Arista does offer some OpenFlow support, their emphasis is on SDN via APIs.

11.4 SOFTWARE VENDORS

The move toward network virtualization has opened the door for software vendors to play a large role in the networking component of the data center. Some of the software vendors that have become significant players in the SDN space include VMware, Microsoft, Big Switch, as well as a number of startups. We will try to put their various contributions into context in the following paragraphs.

VMware, long a dominant player in virtualization software for the data center, has contributed significantly to the interest and demand for SDN in the enterprise. VMware boldly altered the SDN landscape when it acquired Nicira. VMware's purchase of Nicira has turned VMware into a networking vendor. Nicira's roots, as we explained in Section 11.1.1, come directly from pioneers in the Open SDN research community.

VMware's current offerings include *Open vSwitch*, (OVS) as well as the *Network Virtualization Platform* (NVP) acquired through Nicira. (NVP is now marketed as VMware NSX.) NVP uses OpenFlow (with some extensions) to program forwarding information into its subordinate OVS switches.

VMware marketing communications claim that SDN is complete with only SDN via Overlays. OpenFlow is their southbound API of choice, but the emphasis is on network virtualization via overlay networks, not on what can be achieved with OpenFlow in generalized networking environments. This is a very logical business position for VMware. The holy grail for VMware is not about academic arguments but about garnering as much of the data center networking market as it can. This is best achieved by promoting VMware's virtualization strengths and avoiding esoteric disputes about one southbound API's virtues versus other approaches.

Other vendors and enterprises have begun to see the need to interoperate with the Nicira solution. Although VMware's solution does not address physical devices, vendors who wish to create overlay solutions that work with VMware environments will likely need to implement these Nicira-specific APIs as well.

While VMware and Cisco were co-definers of the VXLAN [10] standard, they now appear to be diverging. Cisco is focused on their ODL and APIC controller strategy, and VMware on NSX. With respect to tunneling technologies, Cisco promotes VXLAN which is designed for software and hardware networking devices, while VMware promotes both VXLAN and STT. STT [11] has a potential performance advantage in the software switch environment customary for VMware. This advantage derives from STT's ability to use the server NIC's TCP hardware acceleration to improve network speed and reduce CPU load.

As a board-level participant in the ONF, Microsoft is instrumental in driving the evolution of OpenFlow. Microsoft's current initiative and effort regarding SDN has been around the Azure public cloud project. Similar to VMware, Microsoft has its own server virtualization software called *Hyper-V* and is utilizing SDN via Overlays in order to virtualize the network as well. Their solution uses NVGRE [12] as the tunneling protocol, providing multitenancy and the other benefits described in Section 8.3.2.

Big Switch Networks was founded in 2010 by Guido Appenzeller with Rob Sherwood as CTO of controller technology, both members of our SDN hall of fame. Big Switch is one of the primary proponents of OpenFlow and Open SDN. Big Switch has Open SDN technology at the device, controller, and application levels. Big Switch created an open source OpenFlow switch code base called Indigo. Indigo is the basis for Big Switch's commercial OpenFlow switch software, which they market as *Switch Light*. The Switch Light initiative is a collaboration of switch, ASIC and SDN software vendors to create a simple and cost-effective OpenFlow-enabled switch. Big Switch provides a version of Switch Light intended to run as a virtual switch, called *Switch Light for Linux*, as well as one targeted for the white-box hardware market, called *Switch Light for Broadcom*. We discuss the white-box switch concept in Section 11.5.

Big Switch provides both open source and commercial versions of an SDN controller. The commercial version is called *Big Network Controller*, which is based on its popular open source controller called *Floodlight*. Big Switch also offers complete SDN solutions, notably *Big Cloud Fabric*, which provides network virtualization through overlays using OpenFlow virtual and physical devices.

There are numerous software startups that are minor players in the SDN space. Both Nicira and Big Switch were startups. Nicira, as we have mentioned, was the target of a major VMware acquisition. Big Switch has received a large amount of venture capital funding. Both of these companies have become major forces on the SDN playing field. There are a number of other SDN software startups that have received varying amounts of funding and in some cases have been acquired. Except for Nicira and Big Switch, we do not feel that any of these have yet to become major voices in the SDN dialogue. Since they have been influential in terms of being recipients of much venture capital attention and investment, and may in the future become major players in SDN, we will discuss in Chapter 14 startups such as Insieme, PLUMgrid, and Midokura and their business ramifications for SDN.

11.5 WHITE-BOX SWITCHES

We earlier defined a white-box switch as a hardware platform that is purpose-built to be easily loaded with an NOS such as Switch Light or OVS. The goal is to create a simple, inexpensive device which can be controlled by an OpenFlow controller and the SDN applications that run on top of it. The control software that network vendors typically put into their devices is largely absent from a white-box switch.

The natural alliances in the white-box switch ecosystem are depicted in Fig. 11.1. Enterprises that spend fortunes on networking equipment are naturally drawn to a technology that would allow them to populate the racks of their mega-data centers with low-cost switching gear. A company like Big Switch that bets its future on the increasing demand for its Big Cloud Fabric due to an explosion in the number of OpenFlow-enabled switches clearly wishes to foster the white-box model [13]. Merchant silicon vendors and ODMs form the nexus of the physical white-box switch manufacturing ecosystem.

The merchant silicon vendors that make the switching chips are increasingly aligned with capabilities in the OpenFlow standards, though this process is unfolding far more slowly than Open SDN enthusiasts would desire. Traditionally, much of the hardware platforms sold by the major NEMs, particularly lower-end devices, are actually manufactured by *Original Device Manufacturers* (ODMs). The ODMs, in turn, are focused on the most cost-effective manufacturing of hardware platforms whose hardware logic largely consists of switching chips from the merchant silicon vendors plus commodity CPUs and memory. Industry consolidation means that the hardware switching platforms look ever more similar. The major NEMs have traditionally distinguished their products by control and management software and marketed those features plus the support afforded by the large organization. Now that the control and management software can be provided by software vendors such as Big Switch, the possibility exists for the marriage of such an NOS with a white-box device. As we explained in Section 6.4, this situation is reminiscent of the PC, tablet, and smartphone markets where ODMs manufacture the hardware platforms, while operating systems, such as Windows and Linux, are loaded onto them in a generic fashion.

DISCUSSION QUESTION

We have said the loading an NOS (e.g., general purpose OpenFlow device software) onto a white-box switch is reminiscent of the Wintel ecosystem in the PC world. Which SDN players play an analogous role to Microsoft in this ballet? To Intel? Thinking in the other direction, provide some examples of PC ODMs that played similar roles to those played by Accton and Quanta in the SDN ecosystem?

Obviously, while this ecosystem intimately involves the merchant silicon vendors, the ODMs, and the software vendors, the role of the traditional NEMs is diminished. It is important to recognize, though, that the white-box switch concept does not readily apply to all networking markets. When the customer is large and sophisticated, such as a major cloud services vendor like Google, the support provided by the traditional NEM is of less value. Many customers, though, will continue to need the technical support that comes from the traditional NEM even if they choose to migrate to the OpenFlow model.

One example of a white-box ecosystem is the Switch Light Initiative formed by Big Switch. As the originator of Switch Light, Big Switch offers its OpenFlow device software to switch manufacturers, with the goal of developing a broader market for its OpenFlow controllers. While conceptually this switch software can be adapted to run with any merchant silicon switching chips, the initial merchant silicon vendor involved is Broadcom, and there is now a version of the Switch Light software available called *Switch Light for Broadcom*, as we mentioned earlier. ODMs are a natural target for this software. The coupling between Switch Light and the white-box switch can be very loose. Delivered with a boot loader like the *Open Network Install Environment* (ONIE) the white-box switch leaves the manufacturing floor agnostic as to with which NOS it will be used. When ultimately deployed at a customer site as part of a Big Cloud Fabric the union between the white-box hardware and the Switch Light NOS is consummated.

The startup Pica8's entire business model is based on a white-box strategy wherein Pica8 pairs the open source OpenFlow software with white-box hardware and sells the bundled package. Their operating system and software run on white-box switching hardware available from multiple ODM partners and the switches are controlled using the OpenFlow-capable OVS open source switching code. We discuss Pica8 further in Section 14.9.1.

Cumulus Networks is another startup that offers software ready-made for white-box hardware from ODMs like Accton and Quanta. The Cumulus focus is closer to the idea of *opening up the device* that we introduced in Section 6.4 than to Open SDN. While an OpenFlow-capable system can be loaded on top of the Cumulus operating system, their system is not coupled to OpenFlow. Indeed Cumulus touts that it is possible to use their system with white-box switches without using a centralized controller at all.

11.6 MERCHANT SILICON VENDORS

Merchant silicon vendors provide specialty chips that are assembled into finished hardware products by NEMs or by ODMs who then sell the bare-metal boxes to NEMs who market the hardware under their own brand, usually with their own software. Merchant silicon vendors are interested in any new approach that increases the volume of chips that they sell, so a higher-volume, lower-cost model for switching or server hardware is in their interest. To this end, merchant silicon vendors who make switching chips that are compatible with OpenFlow have been naturally interested in SDN and, in particular, in the white-box switch ecosystem. Two major merchant silicon vendors who have been particularly active in the white-box arena are Intel and Broadcom.

Intel is a strong proponent of network device and server NICs that are designed to handle the flow matching and processing needs of OpenFlow 1.1 and beyond. This Intel strategy is focused on their *Data Plane Development Kit* (DPDK) which we introduced in Section 6.4.

For many years Broadcom has been a vendor of switching chips that ODMs have used to build wired switches. Broadcom's dominance in this area is evidenced by the fact that Big Switch's Switch Light currently comes in one version for hardware devices and that version is called *Switch Light for Broadcom*.

A lesser known player in merchant silicon for SDN is Mellanox. Mellanox, long known for its InfiniBand products, has also entered the market for OpenFlow-enabled switching silicon [14,15]. We explained in Section 5.11 that the most recent versions of OpenFlow have surpassed the ability of extant silicon to support the full feature-set of those specifications. It is a widely held belief that the only real solution to this is to design switching chips specifically to support advanced versions of OpenFlow rather than trying to adapt older designs to do something for which they were not designed. As of this writing, Broadcom, Intel, Mellanox [16], and Corsa [17] all offer commercial silicon supporting OpenFlow 1.3.

11.7 ORIGINAL DEVICE MANUFACTURERS

ODMs are focused on the most cost-effective manufacturing of hardware platforms whose hardware logic is mostly embodied in switching chips from the merchant silicon vendors and commodity CPUs and memory. They largely tend to be Taiwanese, Korean, and Chinese low-cost manufacturers. They excel at high-volume, low-cost manufacturing. They have traditionally relied on their NEM customers to provide end-customer support and to develop complex sales channels. Because of this, they have been relegated to a relatively low-margin business of selling bare-metal hardware to NEMs who brand these boxes and sell them through their mature marketing and support organizations. The ODMs desire to move up the value chain and enter a higher margin business model closer to the customer. This process should be aided by customers who are less reliant on NEMs and would rather purchase hardware directly from the ODMs with the expectation of lower CAPEX costs. Two examples of ODMs that are particularly interested in the white-box switch model for SDN are Accton and Quanta.

DISCUSSION QUESTION

Fig. 11.1 depicts synergy between software vendors, merchant silicon vendors, and the ODMs that manufacture white-box switches. Describe the ecosystem that results in this synergy.

11.8 CLOUD SERVICES AND SERVICE PROVIDERS

A significant amount of the momentum behind SDN has come from large customers who purchase networking gear from the likes of Cisco, Juniper, Brocade, and others. These businesses are interested in stimulating the evolution of networking toward something more functional and cost-effective. As a consequence, these companies have made significant contributions to SDN over the last few years.

There are two subcategories of these businesses that have displayed the greatest interest in SDN: cloud services and carriers. Cloud services companies such as Google started by providing public Internet access to specialized data that was a target of wide consumer interest. The carriers traditionally provided network infrastructure. Increasingly, though, both categories of enterprise offer *Everything as a Service* (XaaS), providing large data centers that offer a vast number of tenants dynamic access to shared compute, storage, and networking infrastructure. Such large data centers have provided the most fertile ground for making SDN inroads. Hence, these two classes of companies have taken prominent roles in the ONF. The synergy between the cloud services, carriers, and the ONF, which we discuss further in Section 11.9.1, was reflected in Fig. 11.1.

Google has intense interest in improving the capabilities and lowering the cost of networking, and has thus created their own simplified set of networking devices which use OpenFlow and a controller to manage their inter-datacenter WAN connections. We described such an example of Google using SDN in the WAN in Section 9.1.2.

NTT has long been involved in SDN and OpenFlow research. NTT has created its own SDN controller called *Ryu* which can network devices using all releases of OpenFlow through V.1.5. Ryu uses the *OpenFlow Configuration and Management Protocol* (OF-Config) [18] for device configuration. Note that OF-Config itself utilizes NETCONF [19] as the transport protocol and YANG as the data model. As described in Section 9.2.3, Verizon has been involved in large SDN proofs of concept related to cloud bursting. Verizon has also been a leader in the related *Network Functions Virtualization* (NFV) technology, as they chair the NFV committee for the *European Telecommunications Standards Institute* (ETSI), which is currently taking the lead in NFV research and standardization [20].

There are other large enterprises such as banks that run large data centers that also have significant interest in SDN even though they are not part of either of the two major categories discussed previously. For example, Goldman Sachs is on the board of the ONF and is very public about their support for OpenFlow.

11.9 STANDARDS BODIES AND INDUSTRY ALLIANCES

In order for new technologies to become widely adopted, standards are required. In this section we will discuss two different kinds of organizations that produce standards related to SDN. The most obvious genre is a true standards body, such as the IETF or IEEE. A less obvious sort is what we refer to here as an *Open Industry Alliance*. Such an alliance is a group of companies with a shared interest surrounding a technology. A good historical example of an industry alliance and a standards body working on the same technology is the WiFi Alliance and the IEEE 802. The WiFi Alliance created important standards documents (e.g., WPA, WPA2) but was an industry alliance first, not a standards body. In the instance of SDN, it is the industry alliances that have taken the lead with standards more so than the standards bodies. The four most important alliances for SDN are the ONF, ODL, ONOS, and OpenStack. The general idea of OpenStack is to create an abstraction layer above compute, network, and storage resources. While the network component of this abstraction layer has led to a relationship between OpenStack and SDN, SDN is not its primary focus, so we will direct our attention first to the ONF, ODL, and ONOS, three industry groups that are indeed laser-focused on SDN.

The ONF and ODL look at SDN from two very different perspectives. The driving force behind the ONF and the standards it creates are the board members, who represent enterprises such as Deutsche Telekom, Facebook, Goldman Sachs, Google, Microsoft, NTT Communications, Verizon, and Yahoo!, as well as some university researchers. There is not a single NEM represented on the board. ODL, on the other hand, was founded by NEMs and looks at SDN as a business opportunity and/or challenge. Fig. 11.2 depicts the board composition of the three main SDN industry alliances. It is noteworthy that the ONOS board does overlap somewhat with each of the other two, yet there is no overlap between ODL and ONF.

It is easy to fall victim to the temptation of thinking that an alliance controlled by NEMs like ODL will favor protecting its members' business interests over innovating in a way that most helps their user community. There are downsides to an enterprise-driven alliance like ONF as well, though.

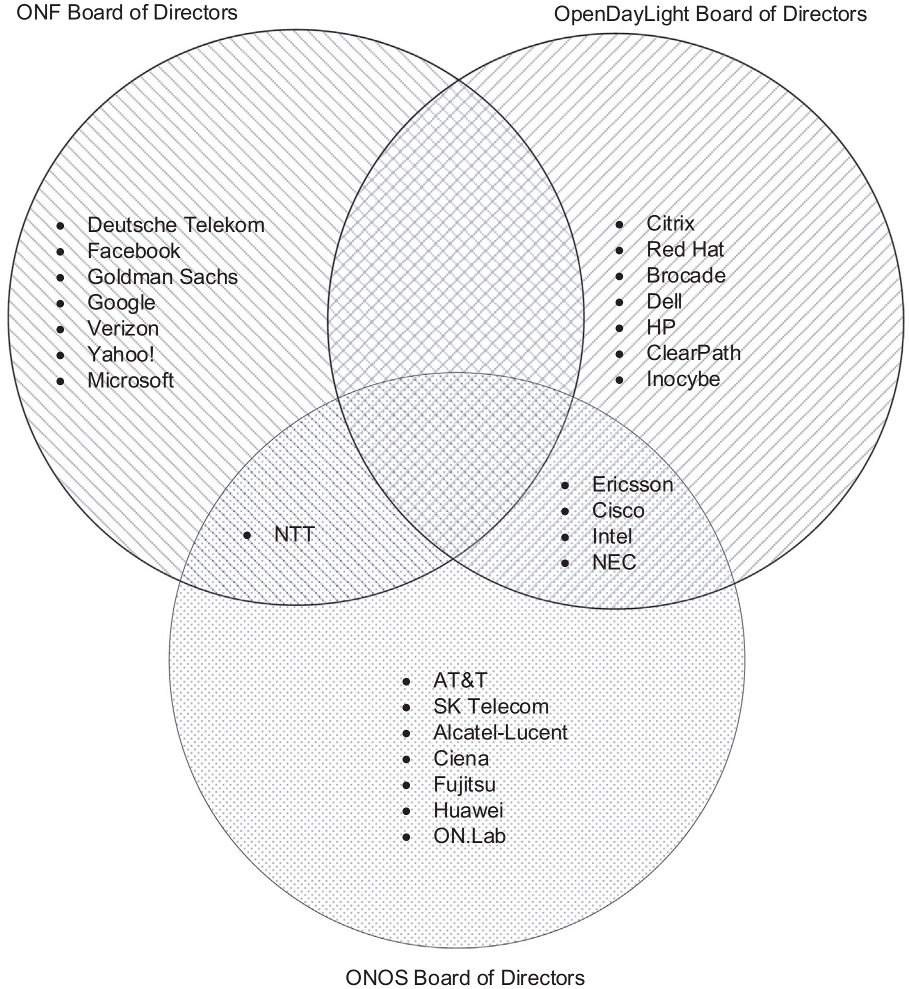

FIG. 11.2

ONF, ODL, and ONOS corporate board membership.

There is the real possibility that the standards that are created will be out of sync with the hardware capabilities of networking devices. To a certain degree this was true with OpenFlow V.1.1 and has become more exaggerated with its later versions. This explains in part the reluctance of the vendors to implement these subsequent revisions of the OpenFlow standard. Conversely, being unencumbered by vendor limitations has resulted in OpenFlow defining what the industry needs, rather than what the vendors can immediately provide. This is the genesis of the conflict between ODL and ONF reflected in Fig. 11.1.

11.9.1 OPEN NETWORKING FOUNDATION

The ONF occupies a preeminent place within the set of standards bodies contributing to SDN. The Open Networking Foundation was created in 2011 and its stated purpose is *the promotion and adoption of Software Defined Networking (SDN) through open standards development* [21]. The ONF is the owner of the OpenFlow standards process. To date, OpenFlow is the most influential work produced by the ONF. The various councils, areas, and working groups active within the ONF as of this writing were shown in Fig. 3.8.

11.9.2 OPENDAYLIGHT

ODL's mission is to *facilitate a community-led, industry-supported open source framework, including code and architecture, to accelerate and advance a common, robust Software Defined Networking platform* [22]. The project is part of the Linux Foundation of Collaborative Projects and boasts many major networking vendors as members (e.g., Brocade, Cisco, IBM, HP, Huawei, Intel, NEC, VMware, and others).

ODL welcomes source code contributions from its members, and has a fairly rigorous process for software review and inclusion. As can be seen by the list of contributing engineers as well as the ODL controller interface, much of the controller software comes from Cisco. In addition to the many Cisco contributors, many other contributors have added software to the ODL open source code base. Plexxi has provided an API allowing the controller and applications to collaborate using an abstraction of the underlying network infrastructure that is independent of the particular switching equipment used. Software to prevent *Distributed Denial of Service* (DDoS) attacks has been contributed by Radware. Ericsson and IBM collaborated with Cisco to provide OpenFlow plugins to the controller. Pantheon has provided a version of OpenFlow 1.3. We provide more details about ODL in Section 13.8.2.

The ONF focuses on defining a specific protocol (OpenFlow) between network devices and a controller to move the control plane from those devices to the controller. ODL focuses not on a single control protocol or on mandating that network devices conform to that protocol. Rather, ODL is focused on providing an open source controller platform, playing a role for SDN controllers much like the role Linux plays in servers. We depict this very different focus between the ONF and ODL consortia in Fig. 11.3. Many different controller-to-device protocols are supported under this umbrella of open-source functionality. Although there was initial skepticism whether ODL would just be a repackaging of Cisco's XNC controller, it has emerged as one of the fastest-growing open source projects in any domain.

11.9.3 ONOS

ONOS is a recent arrival on the SDN scene, but its presence has drastically altered the SDN controller landscape compared to just a few years ago. While many controllers have played their part in the evolution of SDN, the only two significant open source controllers as of this writing are ODL and ONOS. As can be seen in Fig. 11.2, ONOS has attracted more board participation from service providers and NEMs focused on that market than does ODL. ONOS is firmly committed to the principles of Open SDN, which is not strictly true of ODL. Whereas ODL has silver, gold, and bronze levels of participation and corresponding influence, members' influence on ONOS is ostensibly a function of their level of participation rather an amount paid for membership. The ONOS mission is

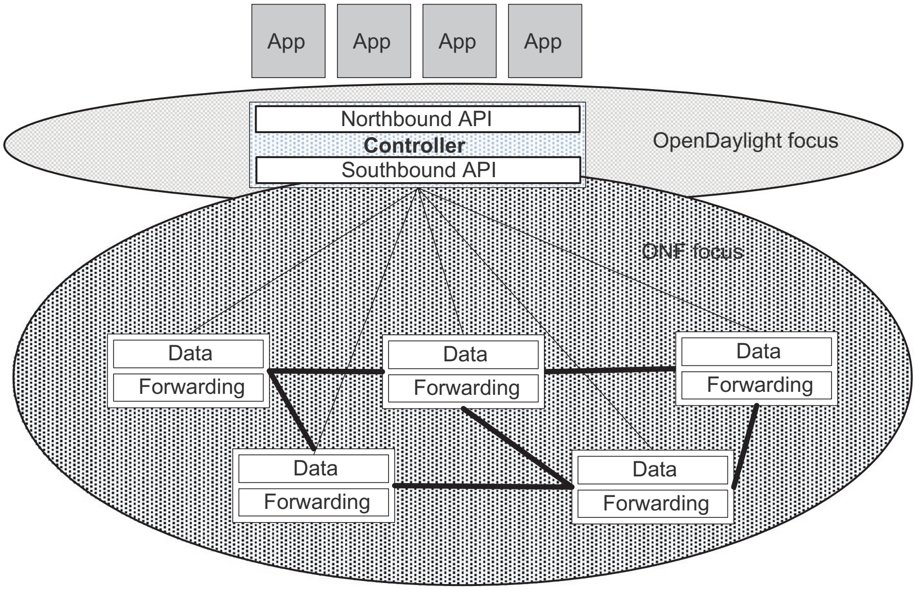

FIG. 11.3

Focus of ONF vs OpenDaylight.

heavily influenced by one of its founding entities, ON.Lab, which, at its core, is a research organization. As we said in Section 11.1.1, Guru Parulkar, the Executive Director of ON.Lab and now ONOS, is strongly opposed to the dilution of SDN from its founding principles. The mission statement *To produce the Open Source Network Operating System that will enable service providers to build real Software Defined Networks* [23], clearly exposes the service provider orientation of this group. ONOS emphasizes the use of OpenFlow and the high reliability features that are required for service provider use. Unlike ODL, it does not prioritize the repurposing of legacy equipment and protocols to achieve SDN goals. Since their controller software was first open-sourced in 2014, the ONOS community has rapidly risen to become an influential player with respect to SDN controllers. We provide more details about ONOS in Section 13.8.3.

DISCUSSION QUESTION

Fig. 11.2 shows that the intersection of the corporate board members of the ONF and ODL is the empty set. Explain how this is a reflection of the different focus of these two organizations.

11.9.4 OpenStack

The OpenStack project was started by Rackspace and NASA in 2010 as an open source IaaS toolset. In a sense, OpenStack can be viewed as the Linux of cloud computing. The interest in this open source project quickly grew, culminating in the establishment in September 2012 of the nonprofit OpenStack

Foundation. The mission of the OpenStack Foundation is to *promote, protect, and empower OpenStack software and its community*. As of this writing, the foundation has more than 6700 member companies spread over 83 countries. The largest current deployment of OpenStack remains in one of its founding companies, Rackspace, which is a major provider of cloud computing.

The general idea of OpenStack is to create an abstraction layer above compute, network, and storage resources. This abstraction layer provides APIs which applications can use to interact with the hardware below, independent of the source of that hardware. The interfaces for compute, storage, and network present pools of resources for use by the applications mentioned previously.

The OpenStack networking definition states that SDN is not required, but that *administrators can take advantage of SDN technology like OpenFlow to allow for high levels of multitenancy and massive scale* [24]. The network virtualization component of OpenStack is called Neutron and, thus, is the component most relevant to our discussion of SDN. Neutron was formerly called Quantum. Neutron provides an application-level networking abstraction. By abstracting the details of the underlying physical network devices, Neutron is intended to provide users of cloud computing with the ability to create overlay networks that are easier to manage and understand by the cloud tenants. It attempts to provide a *Network-as-a-Service* (NaaS), by allowing the cloud tenants to interconnect *virtual network interfaces* (vNICs) [25]. The actual mapping of these virtual network interfaces to the physical network requires the use of Neutron plugins. This is where the relationship between OpenFlow and OpenStack exists. One Neutron plugin could be an interface to an OpenFlow controller that would control physical switches [26]. ODL currently offers a Neutron northbound API. We discuss OpenStack architecture further in Section 13.12.

Although this link between OpenStack and SDN is thin, OpenStack's impact as an industry alliance means that it is an important SDN player despite the peripheral role played by SDN in the overall OpenStack architecture.

11.9.5 OpenSwitch

OpenSwitch [27] is a new open source community started by HP in 2015 with the goal of providing high reliability open source SDN switch code. In this sense it is in direct competition with Switch Light and OVS. We describe the organization's founding members, its goals and licensing in Section 13.7. As it is very new, it is difficult to assess at this point how significant a player this consortium is likely to be, but the strong push it is getting from HP augurs well for its future.

11.9.6 THE OPEN SOURCE SDN COMMUNITY

The *Open Source SDN* (OSSDN) community [28] was introduced in 2015 and differs from the other open source communities we have mentioned in this section in that its participants are not companies but individuals. As of this writing, OSSDN's only funding is from its sponsor, the ONF. Rather than trying to shape a policy that will influence the direction of an industry, its goal is to provide an online gathering place for individuals that wish to contribute to open source projects related to SDN. We describe the OSSDN projects that are currently active in Section 13.9.1. The fact that it is *the* open source community sponsored by the ONF implies that this organization will likely play a significant role on the SDN stage.

11.9.7 IETF

As a late arrival to the SDN playground, the IETF now has a *software-driven networks birds of a feather* (BoF) group and an SDN research group (SDNRG). While there are no current standardization efforts in the IETF directed solely at SDN, the IETF is active in standards that are indirectly related to SDN, such as the existing standards for network virtualization including VXLAN, NVGRE, and STT, which we discussed in Section 8.3 as SDN technologies for overlays and tunneling. Others include the *Path Computation Element* (PCE) [29] and *Network Virtualization Overlays* (nvo3) [30] standards. While the IEEE was not active in the early days of SDN, this important standards body now hosts the IEEE SDN initiative [31], so we expect to see more activity emanating from it in the near future.

11.10 CONCLUSION

In the course of presenting the major players in SDN, this chapter reads somewhat like a *Who's Who* in networking. At times it does appear that the world is jumping on the SDN bandwagon in order to not be left behind. We must temper this by saying that not every NEM or even every large enterprise customer is certain that SDN lies in their future. As an example, for all of the enthusiasm for SDN emanating from Google and other cloud services enterprises, Amazon is notable by its absence from any type of membership whatsoever in the ONF and by their relative silence about building their own SDN solution. Amazon is a huge enterprise with large data centers and the need for the advances in networking technology that have the rest of the industry talking about SDN, and one would expect them to have similar mega-datacenter needs as Google and Yahoo! The industry consensus [32] is that Amazon is indeed using SDN in some form for its enormous *Amazon Web Services* (AWS) business, but is doing so in stealth mode. Only time will tell whether Amazon and other SDN backbenchers turn out to be latecomers to the SDN party or whether they were wise to be patient during the *peak of unreasonable expectations* that may have occurred with respect to SDN.

We have stated more than once in this work that openness is a key aspect of what we define as SDN. In formulating this chapter on the key players in SDN, however, it was not possible to talk about open source directly as it is not an entity, and thus not within the scope of this chapter. Indeed many of the SDN players we have discussed here have been significant largely *because* of their open source contributions to SDN. In any event, openness and open source are key facets of SDN as we have defined it and, as such, Chapter 13 focuses entirely on open source software related to SDN. First, though, in the next chapter we provide a tutorial on writing Open SDN applications.

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