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Evolving Technologies Study Guide

By: Nicholas J. Russo

CCIE™ #42518 (RS/SP)

CCDE™ #20160041

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About the Author

Nicholas (Nick) Russo holds active CCIE certifications in Routing and Switching and Service Provider, as well as CCDE. Nick authored a comprehensive study guide for the CCIE Service Provider version 4 examination and this document provides updates to the written test for all CCIE/CCDE tracks. Nick also holds a Bachelor's of Science in Computer Science, and a minor in International Relations, from the Rochester Institute of Technology (RIT). Nick lives in Maryland, USA with his wife, Carla, and daughter, Olivia. For updates to this document and Nick's other professional publications, please follow the author on Twitter with the handle **@nickrusso42518**.

Technical Reviewers: Guilherme Loch Góes, Nathan Wall, and many from the RouterGods community.

Author's Notes

This book is designed for any CCIE track (as well as the CCDE) that introduces the "Evolving Technologies" section of the blueprint for the written qualification exam. It is not specific to any examination track and provides an overview of the three key evolving technologies: Cloud, Software Defined Networking (SDN), and Internet of Things (IoT). More detailed references are included at the end of each chapter; candidates are encouraged to review those resources. *Italic text* represents cited text from another not created by the author. This is typically directly from a Cisco document, which is appropriate given that this is a summary of Cisco's vision on the topics therein.

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1. Cloud

Cisco has defined cloud as follows:

IT resources and services that are abstracted from the underlying infrastructure and provided "on-demand" and "at scale" in a multitenant environment.

Cisco identifies three key components from this definition that differentiate cloud deployments from ordinary data center (DC) outsourcing strategies:

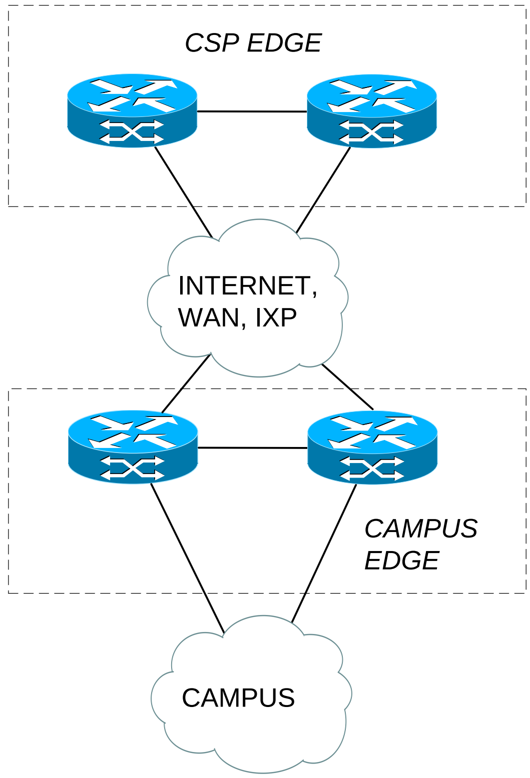
a. *"On-demand" means that resources can be provisioned immediately when needed, released when no longer required, and billed only when used.*
b. *"At-scale" means the service provides the illusion of infinite resource availability in order to meet whatever demands are made of it.*
c. *"Multitenant environment" means that the resources are provided to many consumers from a single implementation, saving the provider significant costs.*

These distinctions are imported for a few reasons. Some organizations joke that migrating to cloud is simple; all they have to do is update their on-premises DC diagram with the words "Private Cloud" and upper management will be satisfied. While it is true that the term "cloud" is often abused, it is important to differentiate it from a traditional private DC. This is discussed next.

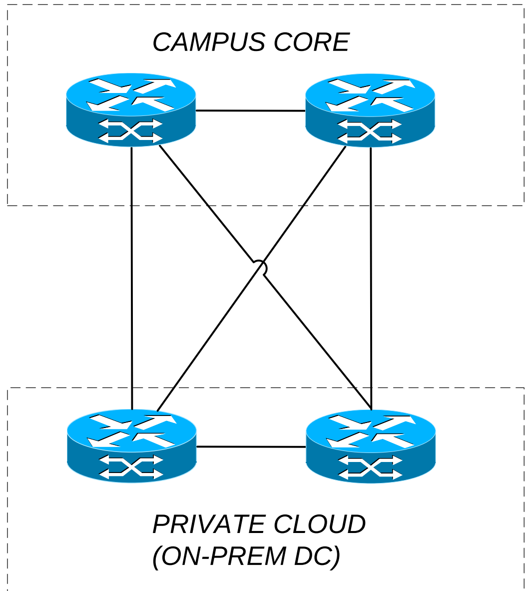
1.1 Compare and contrast Cloud deployment models

Cloud architectures generally come in four variants:

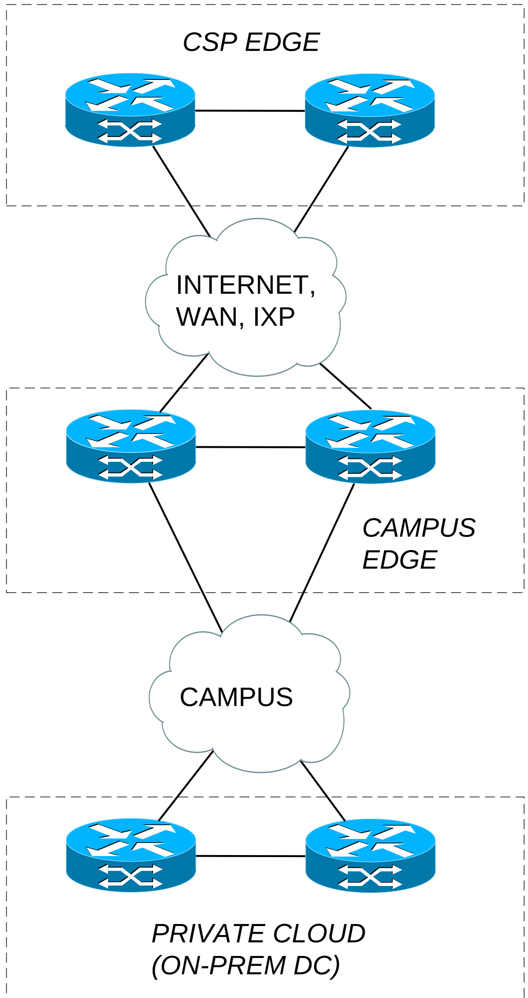
a. **Public**: Public clouds are generally the type of cloud most people think about when the word "cloud" is spoken. They rely on a third party organization (off-premise) to provide infrastructure where a customer pays a subscription fee for a given amount of compute/storage, time, data transferred, or any other metric that meaningfully represents the customer's "use" of the cloud provider's shared infrastructure. Naturally, the supported organizations do not need to maintain the cloud's physical equipment. This is viewed by many businesses as a way to reduce capital expenses (CAPEX) since purchasing new DC equipment is unnecessary. It can also reduce operating expenses (OPEX) since the cost of maintaining an on-premise DC, along with trained staff, could be more expensive than a public cloud solution. A basic public cloud design is shown on the following page; the enterprise/campus edge uses some kind of transport to reach the public cloud network.



b. **Private**: Like the joke above, this model is like an on-premises DC except must supply the three key ingredients identified by Cisco to be considered a “private cloud”. Specifically, this implies automation/orchestration, workload mobility, and compartmentalization must all be supported in an on-premises DC to qualify. The organization is responsible for maintaining the cloud’s physical equipment, which is extended to include the automation and provisioning systems. This can increase OPEX as it required trained staff. Like the on-premises DC, private clouds provide application services to a given organization and multi-tenancy is generally limited to business units or projects/programs within that organization (as opposed to entirely different customers). The diagram on the following page illustrates a high-level example of a private cloud.



c. **Virtual Private**: A virtual private cloud is a combination of public and private clouds. An organization may decide to use this to offload some (but not all) of its DC resources into the public cloud, while retaining some things in-house. This can be seen as a phased migration to public cloud, or by some skeptics, as a non-committal trial. This allows a business to objectively assess whether the cloud is the" right business decision". This option is a bit complex as it may require moving workloads between public/private clouds on a regular basis. At the very minimum, there is the initial private-to-public migration which occurs no matter what, and this could be time consuming, challenging, and expensive. This is sometimes called a "hybrid cloud" as well and could, in fact, represent a business' IT end-state. The diagram on the following page illustrates a high-level example of a virtual-private (hybrid) cloud.



d. **Inter-cloud**: Like the Internet (a non-hierarchical interconnection of various autonomous systems to exchange network reachability information), Cisco suggests that, in the future, the contiguity of cloud computing may extend between many third-party organizations. This is effectively how the Internet works; a customer signs a contract with a given service provider (SP) yet has access to several thousand other AS resources on the Internet. The same concept could be applied to cloud and this is an active area of research for Cisco.

Below is a based-on-a-true-story discussion that highlights some of the decisions and constraints relating to cloud deployments.

a. An organization decides to retain their existing on-premises DC for legal/compliance reasons. By adding automation/orchestration and multi-tenancy components, they are able to quickly increase and decrease virtual capacity. Multiple business units or supported organizations are free to adjust their security policy requirements within the shared DC in a manner that is secure and invisible to other tenants; this is the result of compartmentalization within the cloud architecture. This deployment would qualify as a "private cloud".

b. Years later, the same organization decides to keep their most important data on-premises to meet seemingly-inflexible Government regulatory requirements, yet feels that migrating a portion of their private cloud to the public cloud is a solution to reduce OPEX. This helps increase the scalability of the systems for which the Government does not regulate, such as virtualized network components or identity services, as the on-premises DC is bound by CAPEX reductions. The private cloud footprint can now be reduced as it is used only for a subset of tightly controlled systems, while the more generic platforms can be hosted from a cloud provider at lower cost. Note that actually exchanging/migrating workloads between the two clouds at will is not appropriate for this organization as they are simply trying to outsource capacity to reduce cost. This deployment could be considered a "virtual private cloud" by Cisco, but is also commonly referred to as a "hybrid cloud".

c. Years later still, this organization considers a full migration to the public cloud. Perhaps this is made possible by the relaxation of the existing Government regulations or by the new security enhancements offered by cloud providers. In either case, the organization can migrate its customized systems to the public cloud and consider a complete decommission of their existing private cloud. Such decommissioning could be done gracefully, perhaps by first shutting down the entire private cloud and leaving it in "cold standby" before removing the physical racks. Rather than using the public cloud to augment the private cloud (like a virtual private cloud), the organization could migrate to a fully public cloud solution.

1.1.1 Infrastructure, platform, and software services (XaaS)

Cisco defines four critical service layers of cloud computing:

a. *Software as a Service (SaaS) is where application services are delivered over the network on a subscription and on-demand basis.* A simple example would be to create a document but not installing the appropriate text editor on a user's personal computer. Instead, the application is hosted "as a service" that a user can access anywhere, anytime, from any machine.

b. Platform as a Service (PaaS) consists of run-time environments and software development frameworks and components delivered over the network on a pay-as-you-go basis. PaaS offerings are typically presented as API to consumers. Similar to SaaS, PaaS is focused on providing a complete development environment for computer programmers to test new applications, typically in the development (dev) phase. Although less commonly used by organizations using mostly commercial-off-the-shelf (COTS) applications, it is a valuable offering for organizations developing and maintaining specific, in-house applications.

c. Infrastructure as a Service (IaaS) is where compute, network, and storage are delivered over the network on a pay-as-you-go basis. The approach that Cisco is taking is to enable service providers to move into this area. This is likely the first thing that comes to mind when individuals think of "cloud". It represents the classic "outsourced DC" mentality that has existed for years and gives the customer flexibility to deploy any applications they wish. Compared to SaaS, IaaS just provides the "hardware", roughly speaking, while SaaS provides both. IaaS may also provide a virtualization layer by means of a hypervisor. A good example of an IaaS deployment could be a miniature public cloud environment within an SP point of presence (POP) which provides additional services for each customer: firewall, intrusion prevention, WAN acceleration, etc.

d. *IT foundation is the basis of the above value chain layers. It provides basic building blocks to architect and enable the above layers.* While more abstract than the XaaS layers already discussed, the IT foundation is generally a collection of core technologies that evolve over time. For example, DC virtualization became very popular about 15 years ago and many organizations spent most of the last decade virtualizing "as much as possible". DC fabrics have also changed in recent years; the original designs represented a traditional core/distribution/access layer design yet the newer designs represent leaf/spine architectures. These are "IT foundation" changes that occur over time which help shape the XaaS offerings, which are always served using the architecture defined at this layer.

1.1.2 Performance and reliability

Assessing the performance and reliability of cloud networks presents an interesting set of trade-offs. For years, network designers have considered creating "failure domains" in the network so as to isolate faults. With routing protocols, this is conceptually easy to understand, but often times difficult to design and implement, especially when considering business/technical constraints. Designing a DC comes with its own set of trade-offs when identifying the "failure domains" (which are sometimes called "availability zones" within a fabric), but that is outside the scope of this document. The real trade-offs with a cloud environment revolve around the introduction of automation. Automation is discussed in detail in section 1.2.1 but the trade-offs are discussed here as they directly influence the performance and reliability of a system. Note that this discussion is typically relevant for private and virtual private clouds, as a public cloud provider will always be large enough to warrant several automation tools.

Automation usually reduces the total cost of ownership (TCO), which is a desirable thing for any business. This is the result of reducing the time (and labor wages) it takes for individuals to "do things": provision a new service, create a backup, add VLANs to switches, test MPLS traffic-engineering tunnel computations, etc. The trade-off is that all software (including the automation system being discussed) requires maintenance, whether that is in the form of in-house development or a subscription fee from a third-party. If in the form of in-house development, software engineers are paid to maintain and troubleshoot the software which could potentially be more expensive than just doing things manually, depending on how much maintenance and unit testing the software requires. Most individuals who have worked as software developers (including the author) know that bugs or feature requests always seem to pop up, and maintenance is continuous for any non-trivial piece of code. Businesses must also consider the cost of the subscription for the automation software against the cost of not having it (in labor wages). Typically this becomes a simple choice as the network grows; automation often shines here. This is why automation is such a key component of cloud environments because the cost of dealing with software maintenance is almost always less than the cost of a large IT staff.

The main takeaway is that automation should be deployed where it makes sense (TCO reduction) and where it can be maintained with a reasonable amount of effort. This is how the performance and reliability of a cloud environment can be maximized. Another key aspect of cloud design is accessibility, which assumes sufficient network bandwidth to reach the cloud environment. A DC that was once located at a corporate site with 2,000 employees was accessible to those employees over a company's campus LAN architecture. Often times this included high-speed core and DC edge layers whereby accessing DC resources was fast and highly available. With public cloud, the Internet/private WAN becomes involved, so cloud access becomes an important consideration.

The following page includes a table that compares access methods, reliability, and other characteristics of the different cloud solutions.

	Public Cloud	Private Cloud	Virtual Private Cloud	Inter-Cloud
Access (private WAN, IXP, Internet VPN, etc)	Often times relies on Internet VPN, but could also use an Internet Exchange (IX) or private WAN	Corporate LAN or WAN, which is often private. Could be Internet-based if SD-WAN deployments (e.g. Cisco IWAN) are considered.	Combination of corporate WAN for the private cloud components and whatever the public cloud access method is.	Same as public cloud, except relies on the Internet as transport between cloud
Reliability (including accessibility)	Heavily dependent on highly-available and high-bandwidth links to the cloud provider	Often times high given the common usage of private WANs (backed by carrier SLAs)	Typically higher reliability to access the private WAN components, but depends entirely on the public cloud access method	Assuming applications are distributed, reliability can be quite high if at least one “cloud” is accessible (anycast)
Fault Tolerance / intra-cloud availability	Typically high as the cloud provider is expected to have a highly redundant architecture	Often constrained by corporate CAPEX; tends to be a bit lower than a managed cloud service given the smaller DCs	Unlike public or private, the networking link between the two is an important consideration for fault tolerance	Assuming applications are distributed, fault-tolerance can be quite high if at least one “cloud” is accessible (anycast)
Performance (speed, etc)	Typically high as the cloud provider is expected to have a very dense compute/storage architecture	Often constrained by corporate CAPEX; tends to be a bit lower than a managed cloud service given the smaller DCs	Unlike public or private, the networking link between the two is an important consideration, especially when applications are distributed across the two clouds	Unlike public or private, the networking link between the two is an important consideration, especially when applications are distributed across the two clouds

1.1.3 Security and privacy

From a purely network-focused perspective, many would argue that public cloud security is superior to private cloud security. This is the result of hiring an organization whose entire business revolves around providing a secure, high-performing, and highly-available network. Business where “the network is not the business” may be less inclined or less interested in increasing OPEX within the IT department, the dreaded cost center. The counter-argument is that public cloud physical security is always questionable, even if the digital security is strong. Should a natural disaster strike a public cloud facility where disk drives are scattered across a large geographic region (tornado comes to mind), what is the cloud provider's plan to protect customer data? What if the data is being stored in a region of the world known to have unfriendly relations towards the home country of the supported business? These are important questions to ask because when data is in the public cloud, the customer's never really know exactly "where" the data is being stored. This uncertainty can be offset by using "availability zones" where some cloud providers will ensure the data is confined to a given geographic region. In many cases, this sufficiently addresses the concern for most customers, but not always. As a customer, it is also hard to enforce and prove this. This sometimes comes with an additional cost, too.

Privacy in the cloud is achieved mostly by introducing multi-tenancy separation. Compartmentalization at the host, network, and application layers ensure that the entire cloud architecture keeps data private; that is to say, customers can never access data from other customers. Sometimes this multi-tenancy can be done as crudely as separating different customers onto different hosts, which use different VLANs and are protected behind different virtual firewall contexts. Sometimes the security is integrated with an application shared by many customers using some kind of public key infrastructure (PKI). Often times maintaining this security and privacy is a combination of many techniques. Like all things, the security posture is a continuum which could be relaxed between tenants if, for example, the two of them were partners and wanted to share information within the same public cloud provider (like a cloud extranet).

The following page compares the security and privacy characteristics between the different cloud deployment options.

	Public Cloud	**Private Cloud**	**Virtual Private Cloud**	**Inter-Cloud**
Digital security	Typically has best trained staff, focused on the network and not much else (network is the business)	Focused IT staff but likely not IT-focused upper management (network is likely not the business)	Coordination between clouds could provide attack surfaces, but isn't wide-spread	Coordination between clouds could provide attack surfaces (like what BGPsec is designed to solve)
Physical security	One cannot pinpoint their data within the cloud provider's network	Generally high as a business knows where the data is stored, breaches notwithstanding	Combination of public and private; depends on application component distribution	One cannot pinpoint their data anywhere in the world
Privacy	Transport from premises to cloud should be secured (Internet VPN, secure private WAN, etc)	Generally secure assuming corporate WAN is secure	Need to ensure any replicated traffic between public/private clouds is protected; generally this is true as the link to the public cloud is protected	Need to ensure any replicated traffic between distributed public clouds is protected; not the responsibility of end-customers, but cloud providers should provide it

1.1.4 Scalability and interoperability

Achieving cloud scalability is often reliant on many components supporting the cloud architecture. These components include the network fabric, the application design, and virtualization/segmentation design, and others. The ability of cloud networks to provide seamless and simple interoperability between applications can be difficult to assess. Applications that are written in-house will probably interoperate better in the private cloud since the third-party provider may not have a simple mechanism to integrate with it. Some cloud providers may not have this problem, but this depends entirely on their network/application hosting software (OpenStack is one example discussed later in this document). If the application is coded "correctly", APIs would be exposed so that additional provider-hosted applications can integrate with the in-house application. Too often, custom applications are written in a silo where no such APIs are presented.

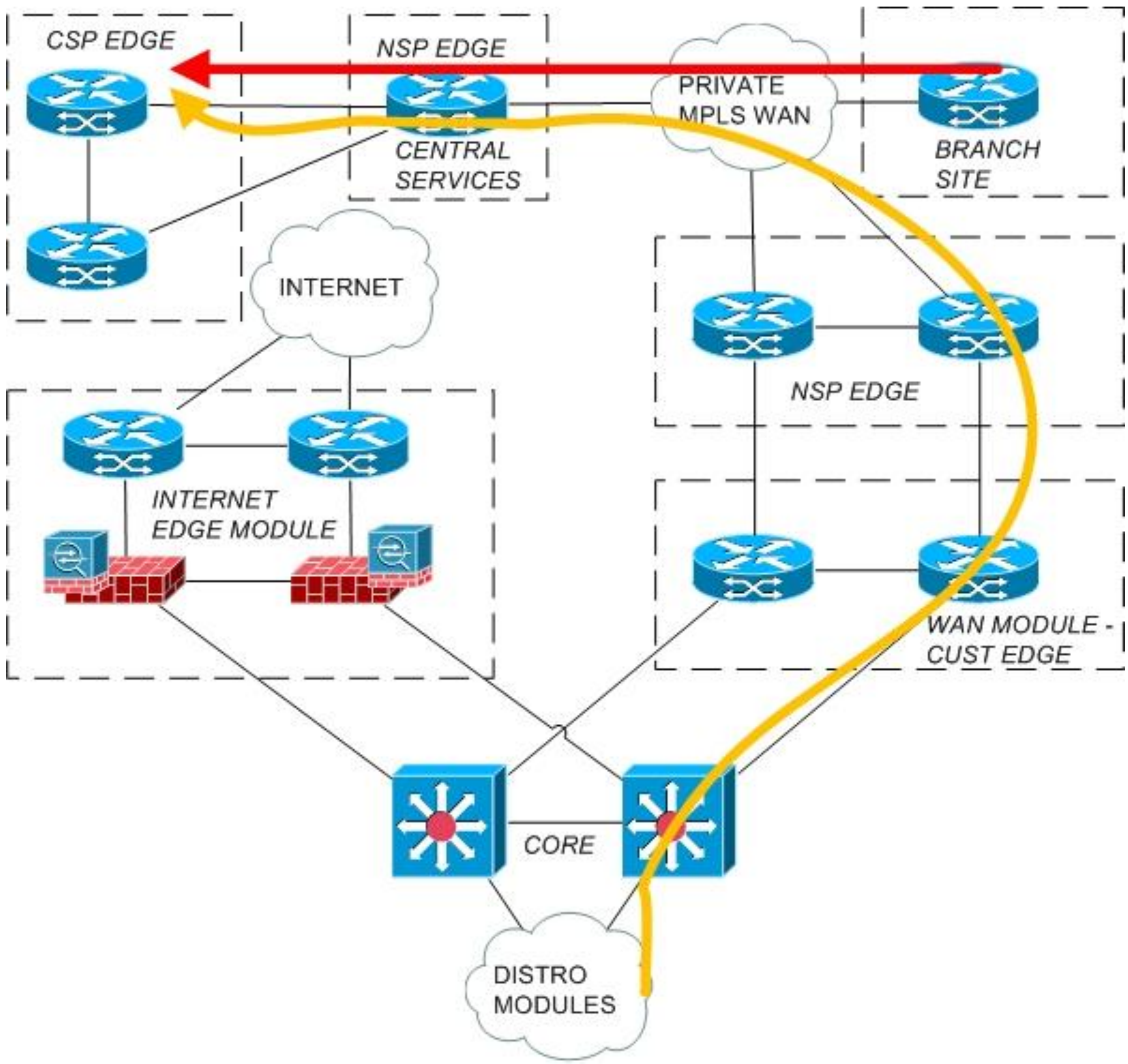
The following page includes a table that briefly discusses the scalability and interoperability considerations across the cloud types.

	Public Cloud	Private Cloud	Virtual Private Cloud	Inter-Cloud
Scalability	Appears to be "infinite" which allows the customer to provision new services quickly	High CAPEX and OPEX to expand it, which limits scale within a business	Scales well given public cloud resources	Highest; massively distributed architecture
Interoperability	Up to the developer to use cloud provider APIs; these are provided as part of the cloud offering	Interoperable with the underlying platform; i.e., one "OpenStack application" should be deployable to another OpenStack instance	Combination of public/private, depending on where the resource is located. Migration between the two could be limited depending on APIs invoked	Up to the developer to use cloud provider APIs; these are provided as part of the cloud offering. Assumes consistent API presentation between different cloud ASes

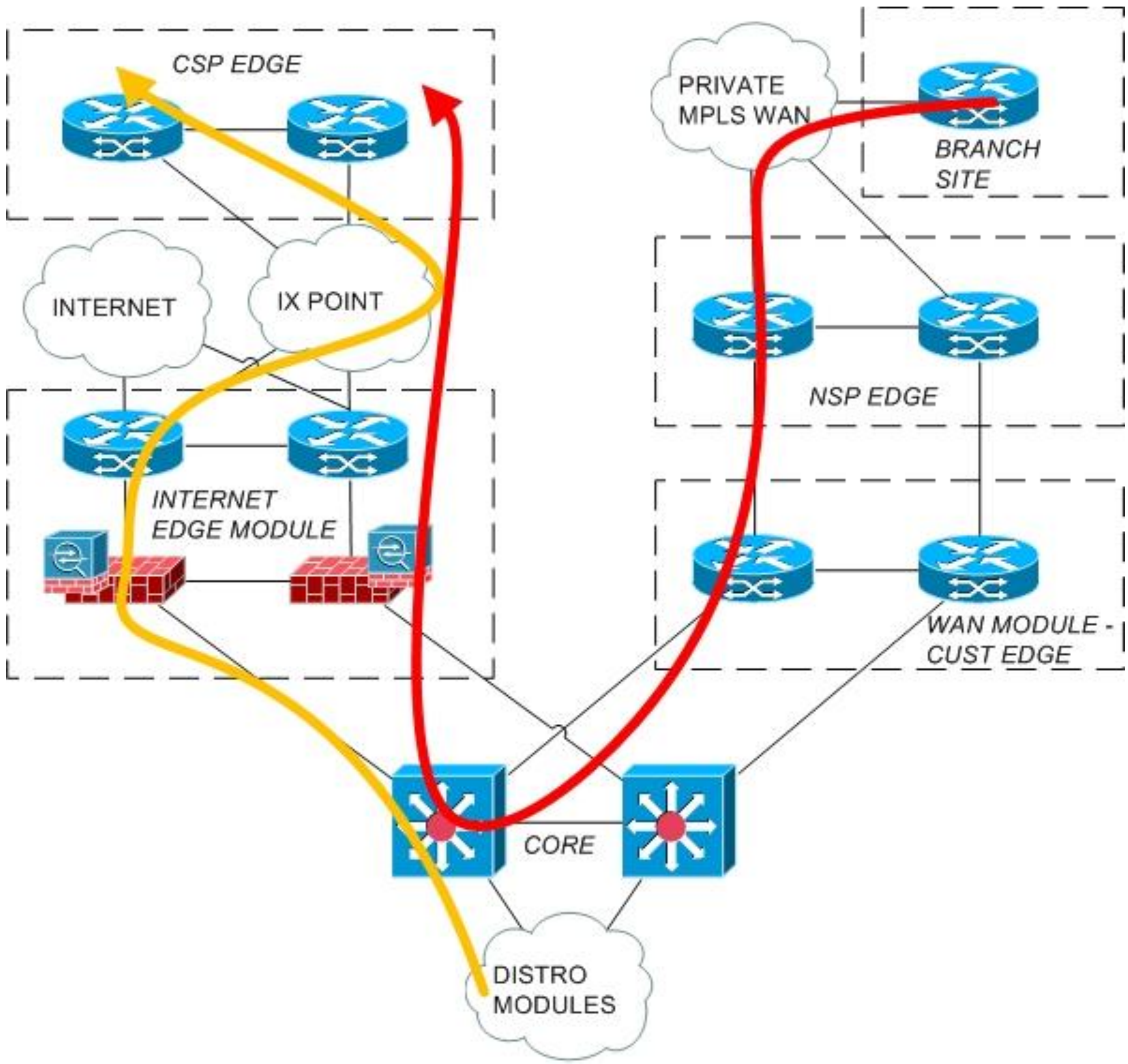
1.2 Describe Cloud implementations and operations

Cloud implementation can be broken into 2 main categories: how the cloud provider works, and how customers connect to the cloud. The second question is more straightforward to answer and is discussed first. There are three main options for connecting to a cloud provider, but this list is by no means exhaustive:

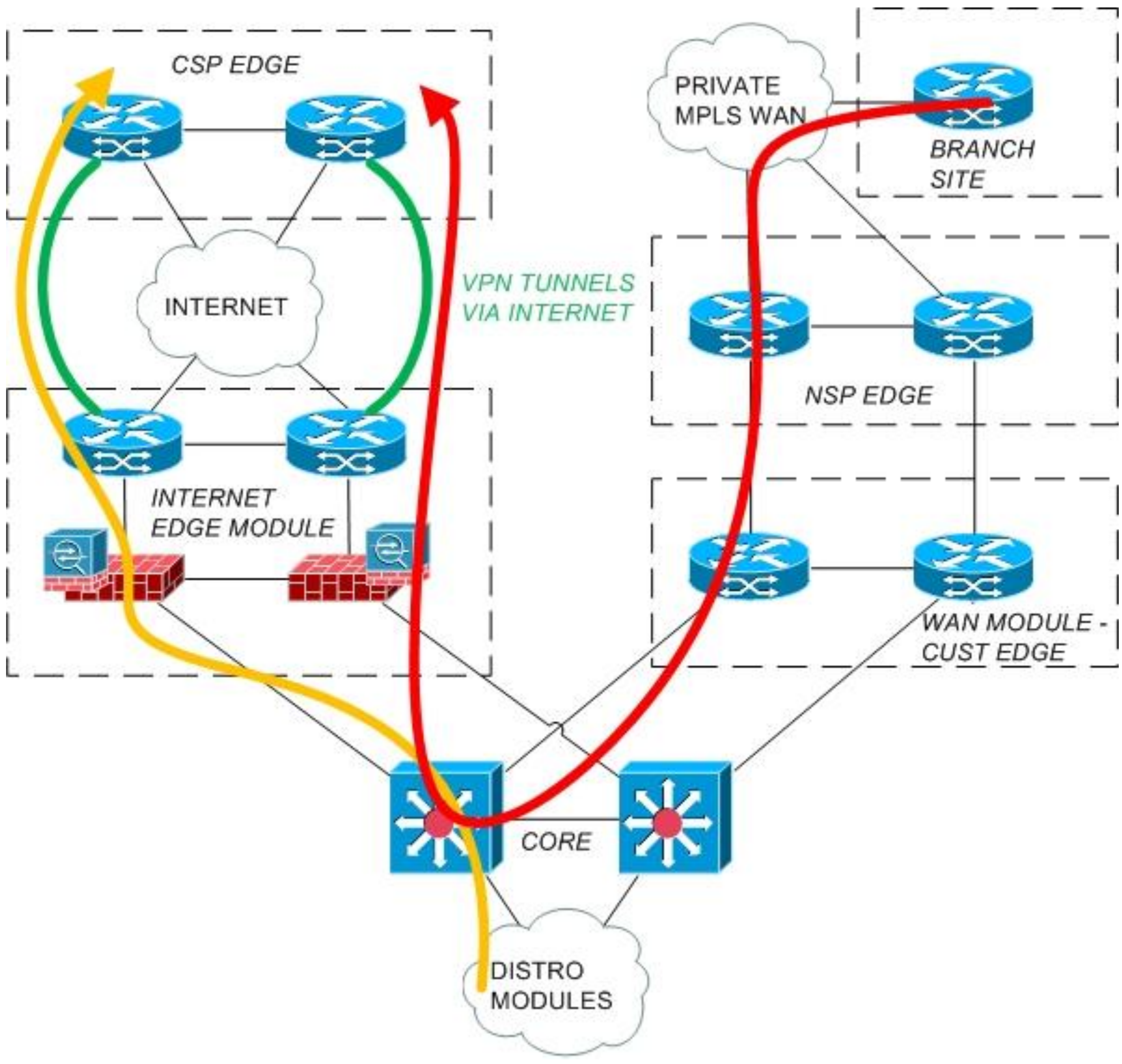
a. **Private WAN (like MPLS L3VPN)**: Using the existing private WAN, the cloud provider is connected as an extranet. To use MPLS L3VPN as an example, the cloud-facing PE exports a central service route-target (RT) and imports corporate VPN RT. This approach could give direct cloud access to all sites in a highly scalable, highly performing fashion. Traffic performance would (should) be protected under the ISP's SLA to cover both site-to-site customer traffic and site-to-cloud/cloud-to-site customer traffic. The ISP may even offer this cloud service natively as part of the service contract; as discussed earlier, certain services could be collocated in an SP POP as well. The private WAN approach is likely to be expensive and as companies try to drive OPEX down, a private WAN may not even exist. Private WAN is also good for virtual private (hybrid) cloud assuming the ISP's SLA is honored and is routinely measuring better performance than alternative connectivity options. Virtual private cloud makes sense over private WAN because the SLA is assumed to be better, therefore the intra-DC traffic (despite being inter-site) will not suffer performance degradation. Services could be spread between the private and public clouds assuming the private WAN bandwidth is very high and latency is very low, both of which would be required in a cloud environment. It is not recommended to do this as the amount of intra-workflow bandwidth (database server on-premises and application/web server in the cloud, for example) is expected to be very high. The diagram below depicts private WAN connectivity assuming MPLS L3VPN. In this design, branches could directly access cloud resources without transiting the main site.



b. **Internet Exchange Point (IXP)**: A customer's network is connected via the IXP LAN (might be a LAN/VLAN segment or a layer-2 overlay) into the cloud provider's network. The IXP network is generally access-like and connects different organizations together for exchange, but typically does not provide transit services between sites like a private WAN. Some describe an IXP as a "bandwidth bazaar" or "bandwidth marketplace" where such exchanges can happen in a local area. A strict SLA may not be guaranteed but performance would be expected to be better than the Internet VPN. This is likewise an acceptable choice for virtual private (hybrid) cloud but lacks the tight SLA typically offered in private WAN deployments. A company could, for example, use internet VPNs for inter-site traffic and an IXP for public cloud access. A private WAN for inter-site access is also acceptable. The diagram below shows a private WAN for branch connectivity and an IXP used for cloud connectivity from the main campus site.



c. **Internet VPN**: By far the most common deployment, a customer creates a secure VPN over the Internet (could be multipoint if outstations required direct access as well) to the cloud provider. It is simple and cost effective, both from a WAN perspective and DC perspective, but offers no SLA whatsoever. Although suitable for most customers, it is likely to be the most inconsistent performing option. While broadband Internet connectivity is much cheaper than private WAN bandwidth (in terms of price per Mbps), the quality is often lower. Whether this is "better" is debatable and depends on the business drivers. Also note that Internet VPNs, even high bandwidth ones, offer no latency guarantees at all. This option is best for fully public cloud solutions since the majority of traffic transiting this VPN tunnel should be user service flows. The solution is likely to be a poor choice for virtual private clouds, especially if workloads are distributed between the private and public clouds. The biggest drawback of the Internet VPN access design is that slow cloud performance as a result of the "Internet" is something a company cannot influence; buying more bandwidth is the only feasible solution. In this example, the branches don't have direct Internet access (but they could), so they rely on an existing private WAN to reach the cloud service provider. This design is shown below.



The answer to the first question detailing how a cloud provider network is built, operated, and maintained is discussed in the remaining sections.

1.2.1 Automation and orchestration

Automation and orchestration are two different things although are sometimes used interchangeably (and incorrectly so). Automation refers to completing a single task, such as deploying a virtual machine, shutting down an interface, or generating a report. Orchestration refers to assembling/coordinating a process/workflow, which is effectively and ordered set of tasks glued together with conditions. For example, deploy this virtual machine, and if it fails, shutdown this interface and generate a report. Automation is to task as orchestration is to process/workflow.

Often times the task to automate is what an engineer would configure using some programming/scripting language such as Java, C, Python, Perl, Ruby, etc. The variance in tasks can be very large since an engineer could be presented with a totally different task every hour. Creating 500 VLANs on 500 switches isn't difficult, but is monotonous, so writing a short script to complete this task is ideal. Adding this script as an input for an orchestration engine could properly insert this task into a workflow. For example, run the VLAN-creation script after the nightly backups but before 6:00 AM the following day. If it fails, the orchestrator can revert all configurations so that the developer can troubleshoot any script errors.

1.2.2 Workload mobility

Workload mobility is a generic goal and has been around since the first virtualized DCs were created. This gives IT administrators an increased ability to share resources amount different workloads within the virtual DC (which could consist of multiple DCs connected across a Data Center Interconnect, or DCI). It also allows workloads to be balanced across a collection of resources. For example, if 4 hosts exist in a cluster, one of them might be performing more than 50% of the computationally-expensive work while the others are underutilized. The ability to move these workloads is an important capability.

It is important to understand that workload mobility is not necessarily the same thing as VM mobility. For example, a workload's accessibility can be abstracted using anycast while the application exists in multiple availability zones (AZ) spread throughout the cloud provider's network. Using Domain Name System (DNS), different application instances can be utilized based on geographic location, time of day, etc. The VMs have not actually moved but the resource performing the workload may vary.

Although this concept has been around since the initial virtualization deployments, it is even more relevant in cloud, since the massively scalable and potentially distributed nature of that environment is abstracted into a single "cloud" entity. Using the cluster example from above, those 4 hosts might not even be in the same DC, or even within the same cloud provider (as could be the case with Inter-cloud). The concept of workload mobility needs to be extended large-scale; note that this doesn't necessarily imply layer-2 extensions across the globe. It simply implies that the workload needs to be moved or distributed differently, which can be solved with geographically-based anycast solutions, for example.

As discussed in the automation/orchestration section above, orchestrating workloads is a major goal of cloud. The individual tasks that are executed in sequence (and conditionally) by the orchestration engine could be distributed throughout the cloud. The task itself (and the code for it) is likely centralized by the targets of those tasks, such as a specific container or storage device, could be distributed.

1.2.3 Troubleshooting and management

One of the fundamental tenets of managing a cloud network is automation. Common scripting languages, such as Python, can be used to automate a specific management task as discussed in an earlier section. Other network device management tools, such as Ansible, allow an administrator to create a custom script and execute it on many devices concurrently. This is one example of the method by which administrators can directly apply task automation in the workplace.

Other protocols and languages, such as NETCONF and YANG, also help automate/simplify network management indirectly. NETCONF (RFC6241) is the protocol by which configurations are installed and changed. YANG (RFC6020) is the modeling language used to represent device configuration and state, much like Extensible Markup Language (XML). Put simply, NETCONF is the transport vessel for YANG information to be transferred from a network management system (NMS) to a network device. Although YANG can be quite complex to humans, it is similar to SNMP; it is simple for machines. YANG is an abstraction away from network device CLIs which promotes simplified management in cloud environments and a progressive migration toward one of the SDN models discussed later in this document. Devices that implement NETCONF/YANG provide a uniform manageability interface which means vendor hardware/software can be swapped in a network without affecting the management architecture, operations, or strategy.

A brief discussion on other data modeling languages is worthwhile. While YANG is quite common, especially when paired with NETCONF, there are easier-to-read alternatives available. One such option is YAML Ain't Markup Language (YAML). It solves a similar problem as YANG since it is primarily used for configuration files, but generally contains a subset of functionality as it was specifically designed to be simpler.

JavaScript Object Notation (JSON) is another data modeling language that is similar to YAML in concept. It was designed to be simpler than traditional markup languages and uses key/value pairs to store information. The "value" of a given pair can be another key/value pair, which enables hierarchical data nesting. The key/value pair structure and syntax is very similar to the "dictionary" data type in Python. JSON is even lighter than YAML and is also commonly used for maintaining configuration files.

Troubleshooting a cloud network is often reliant on real-time network analytics. Collecting network performance statistics is not a new concept, but designing software to intelligently parse, correlate, and present the information in a human-readable format is constantly evolving. With a good analytics engine, the NMS can move/provision flows around the network (assuming the network is both disaggregated and programmable) to resolve any problems. For problems that cannot be resolved automatically, the issues are brought to the administrator's attention using these engines. The administrator can use other troubleshooting tools or NMS features to isolate and repair the fault.

1.2.4 OpenStack components

Before discussing the OpenStack components, background information on OpenStack is provided below. Although OpenStack seems similar to a hypervisor, it adds additional abstractions for virtual instances to reduce the management burden on administrators. OpenStack is part of the motion that technology is moving "from virtual Machines (VM) to APIs". VMs allow users to dynamically instantiate a server abstracted from physical resources, which has been popular for years. The idea of cloud computing (and specifically OpenStack) is to extend that abstraction to ALL resources (compute, storage, network, management, etc). All of these things could be managed through APIs rather than vendor-specific prompts and user interfaces, such as GUIs, CLIs, etc.

The fundamental idea is to change the way IT is consumed (including compute, storage, and network). The value proposition of this change includes increasing efficiency (peak of sums, not sum of peaks) and on-demand elastic provisioning (faster engineering processes). For cost reduction in both CAPEX and OPEX, the cost models generally resemble "pay for what you use". A customer can lease the space from a public cloud provider for a variable amount of time. In some cases, entire IT shops might migrate to a public cloud indefinitely. In others, a specific virtual workload may need to be executed one time for 15 minutes in the public cloud since some computationally-expensive operations may take too long in the on-premises DC. "Cloud bursting" is an example of utilizing a large amount of cloud resources for a very short period of time, perhaps to reduce/compress a large chunk of data, which is a one-time event.

OpenStack releases are scheduled every 6 months and many vendors from across the stack contribute to the code. The entire goal is to have an open-source cloud computing platform; while it may not be as feature-rich as large-scale public cloud implementations, it is considered a viable and stable alternative. OpenStack is composed of multiple projects (improved maintainability) which follow a basic process:

a. **External**: The idea phase
b. **Incubated**: Project requirements, migrate to OpenStack after 2 milestones of incubation
c. **Integrated**: Release as part of OpenStack

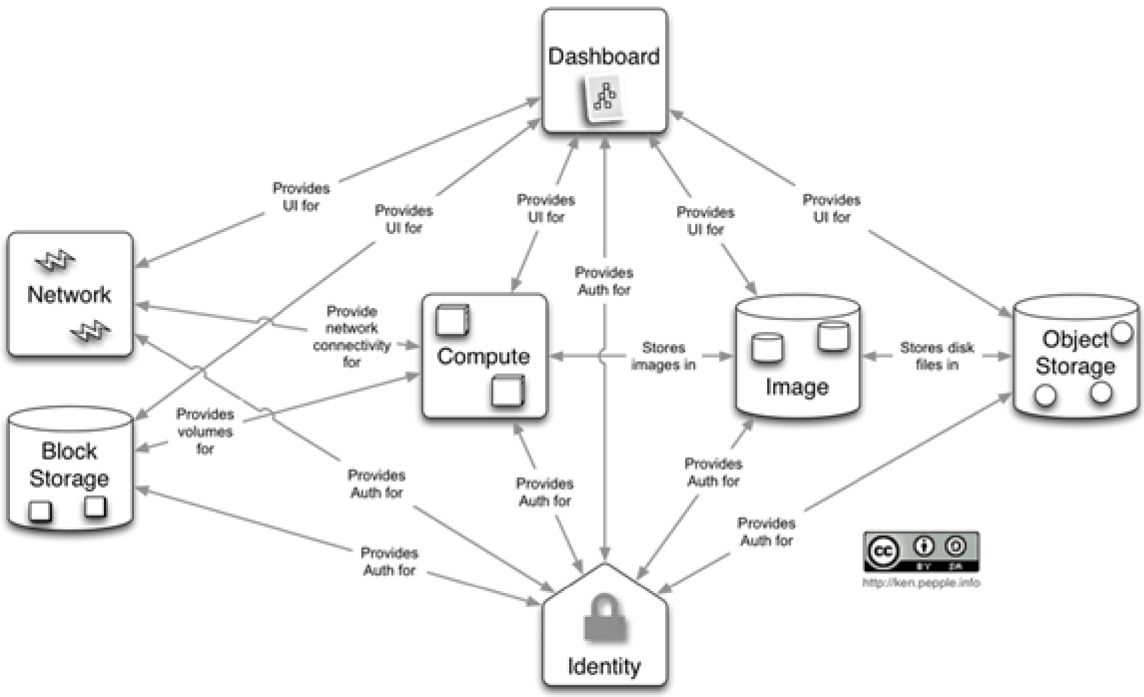
OpenStack has approximately 18 components which are discussed briefly below. The components have code-names for quick reference within the OpenStack community; these are included in parenthesis. Many of the components are supplementary and don't comprise core OpenStack deployments, but can add value for specific cloud needs. Note that OpenStack compares directly to existing public cloud solutions offered by large vendors, except is open source with all code being available online.

a. **Compute (Nova)**: Fabric controller (the main part of an IaaS system). Manages pools of computer resources. A compute resource could be a VM, container, or bare metal server. Side note: Containers are similar to VMs except they share a kernel. They are otherwise independent, like VMs, and are considered a lighter-weight yet secure alternative to VMs.
b. **Networking (Neutron)**: Manages networks and IP addresses. Ensures the network is not a bottleneck or otherwise limiting factor in a production environment. This is technology-agnostic network abstraction which allows the user to create custom virtual networks, topologies, etc. For example, virtual network creation includes adding a subnet, gateway address, DNS, etc.
c. **Block Storage (Cinder):** Manages creation, attaching, and detaching of block storage devices to servers. This is not an implementation of storage itself, but provides as API to access that storage. Many storage appliance vendors often have a Cinder plug-in for OpenStack integration;

this ultimately abstracts the vendor-specific user interfaces from the management process. Storage volumes can be detached and moved between instances (an interesting form of file transfer, file example) to share information and migrate data between projects.

d. **Identity (Keystone):** Directory service contains users mapped to services they can access. Somewhat similar to group policies applied in corporate deployments. Tenants are stored here which allows them to access resources/services within OpenStack; commonly this is access to the OpenStack Dashboard (Horizon) to manage an OpenStack environment.
e. **Image (Glance):** Provides discovery, registration, and delivery services. These images are like ordinary images to template new virtual services.
f. **Object Storage (Swift):** Storage system with built-in data replication and integrity. Objects and files are written to disk using this interface which manages the I/O details. Scalable and resilient storage for all objects like files, photos, etc. This means the customer doesn't have to deploy a block-storage solution themselves, then manage the storage protocols (iSCSI, NFS, etc).
g. **Dashboard (Horizon):** The GUI for administrators and users to access, provision, and automate resources. The dashboard is based on Python Django framework and is layered on top of service APIs. Logging in relies on Keystone for identity management which secures access to the GUI. The dashboard supports different tenants (business units, groups/teams, customers, etc) with separate permissions and credentials; this is effectively role-based access control. The GUI provides the most basic/common functionality for users without needing CLI access, which is supported for advanced functions. "Security group" abstractions to enforce access control (often need to configure this before being able to access the new instances).
h. **Orchestration (Heat):** Service to orchestrate multiple cloud applications via templates using a variety of APIs.
i. **Workflow (Mistral):** Manages user-created workflows which can be triggered manually or by some event.
j. **Telemetry (Ceilometer):** Provides a Single Point of Contact for billing systems used within the cloud environment.
k. **Database (Trove):** This is a Database-as-a-service provisioning engine.
l. **Elastic Map Reduce (Sahara):** Automated way to provision Hadoop clusters, like a wizard.
m. **Bare Metal (Ironic):** Provisions bare metal machines rather than virtual machines.
n. **Messaging (Zaqar):** Cloud messaging service for Web Developments (full RESTful API) used to communicate between SaaS and mobile applications.
o. **Shared File System (Manila):** Provides an API to manage shares in a vendor agnostic fashion (create, delete, grant/deny access, etc).
p. **DNS (Designate):** Multi-tenant REST API for managing DNS (DNS-as-a-service).
q. **Search (Searchlight):** Provides search capabilities across various cloud services and is being integrated into the Dashboard.
r. **Key Manager (Barbican):** Provides secure storage, provisioning, and management of secrets (passwords).

The key components of OpenStack and their interactions are depicted on the following page. The source of this image is included in the references as it was not created by the author.



1.3 Resources and References

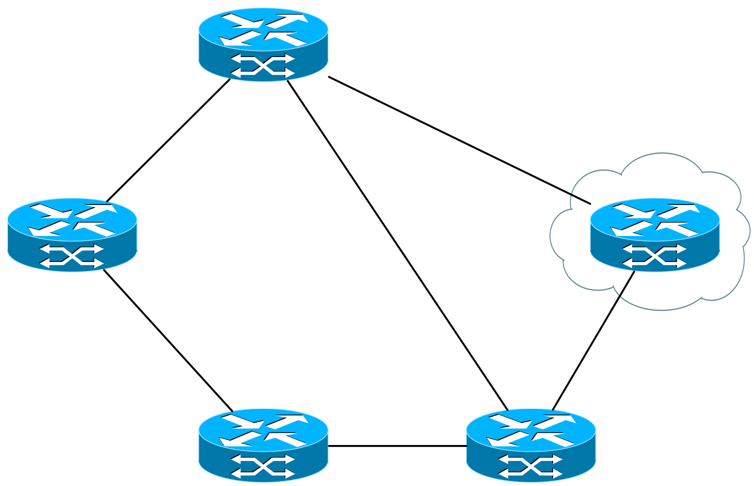
http://www.cisco.com/c/dam/en_us/solutions/industries/docs/gov/CiscoCloudComputing_WP.pdf
https://en.wikipedia.org/wiki/OpenStack#Components
http://www.cisco.com/c/en/us/solutions/cloud/overview.html
http://www.unleashingit.com/
www.cisco.com/go/cloud
https://www.openstack.org/software/
Understanding Cisco Cloud Fundamentals
Designing Networks and Services for the Cloud
http://getcloudify.org/2014/07/18/openstack-wiki-open-cloud.html

2. Network programmability [SDN]

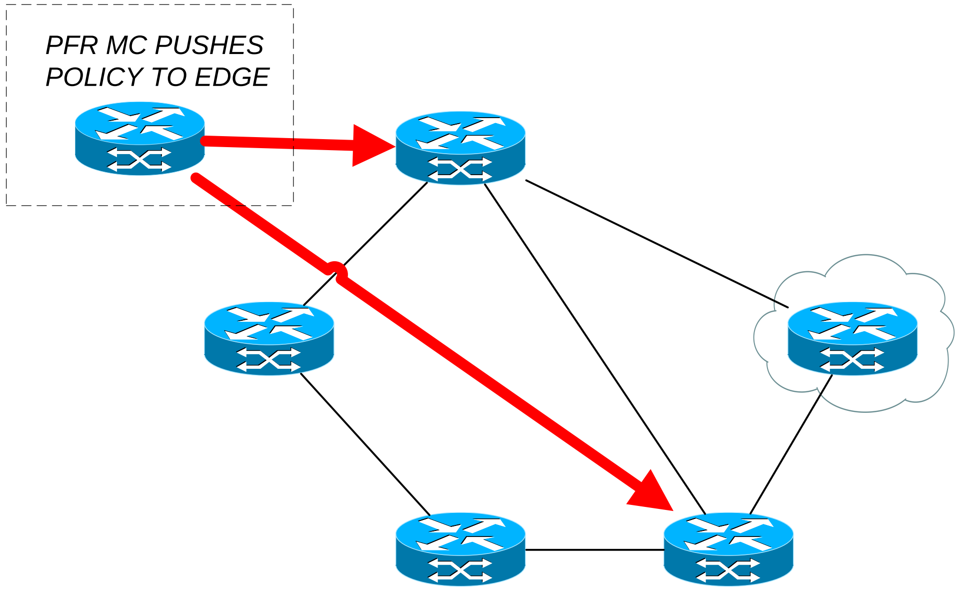
Software-Defined Networking (SDN) is a concept that networks can be both programmable and disaggregated concurrently, ultimately providing additional flexibility, intelligence, and customization by the network administrators. Because the definition of SDNs varies so widely within the network community, it should be thought of as a continuum of different models rather than a single, prescriptive solution.

There are four main SDN models as defined in *"The Art of Network Architecture: Business-Driven Design" by Russ White and Denise Donohue (Cisco Press 2015).* The models are discussed briefly below.

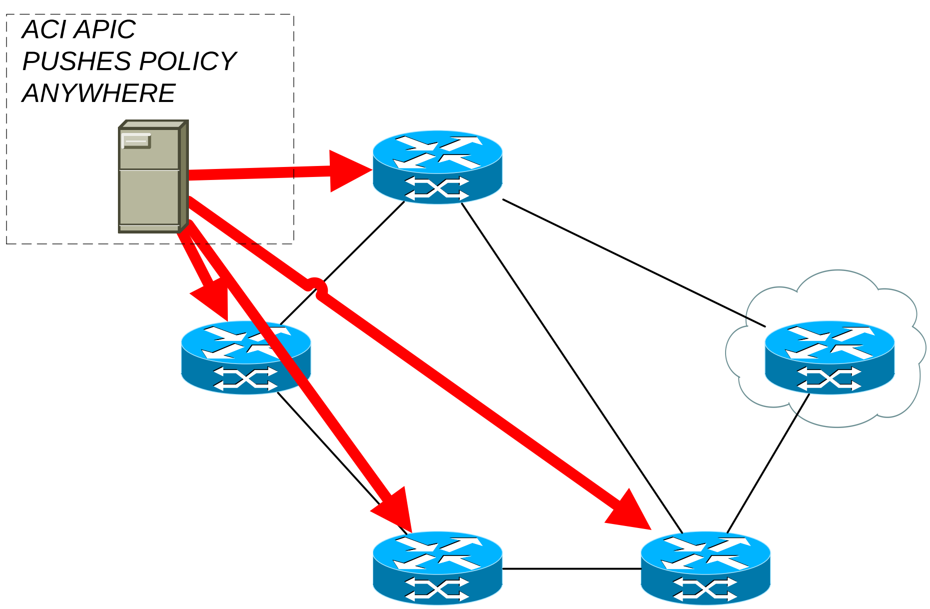
a. **Distributed**: Although not really an "SDN" model at all, it is important to understand the status quo. Network devices today each have their own control-plane components which rely on distributed routing protocols (such as OSPF, BGP, etc). These protocols form paths in the network between all relevant endpoints (IP prefixes, etc). Devices typically do not influence one another's routing decisions individually as traffic is routed hop-by-hop through the network without centralized oversight. This model totally distributes the control-plane across all devices. Such control-planes are also autonomous; with minimal administrative effort, they often form neighborships and advertise topology and/or reachability information. Some of the drawbacks include potential routing loops (typically transient ones during periods of convergence) and complex routing schemes in poorly designed/implemented networks. The diagram below depicts several routers each with their own control-plane and no centralization.



b. **Augmented**: This model relies on a fully distributed control-plane by adding a centralized controller that can apply policy to parts of the network at will. Such a controller could inject shorter-match IP prefixes, policy-based routing (PBR), security features (ACL), or other policy objects. This model is a good compromise between distributing intelligence between nodes to prevent singles points of failure (which a controller introduces) by using a known-good distributed control-plane underneath. The policy injection only happens when it "needs to", such as offloading an overloaded link in a DC fabric or from a long-haul fiber link between two points of presence (POPs) in an SP core. Cisco's Performance Routing (PfR) is an example of the augment model. Another example includes offline path computation element (PCE) servers for automated MPLS TE tunnel creation. In both cases, a small set of routers (PfR border routers or TE tunnel head-ends) are modified, yet the remaining routers are untouched. This model has a lower impact on the existing network because the wholesale failure of the controller simply returns the network to the distributed model, which is known to work "well enough" in many cases. The augmented model is depicted on the following page.

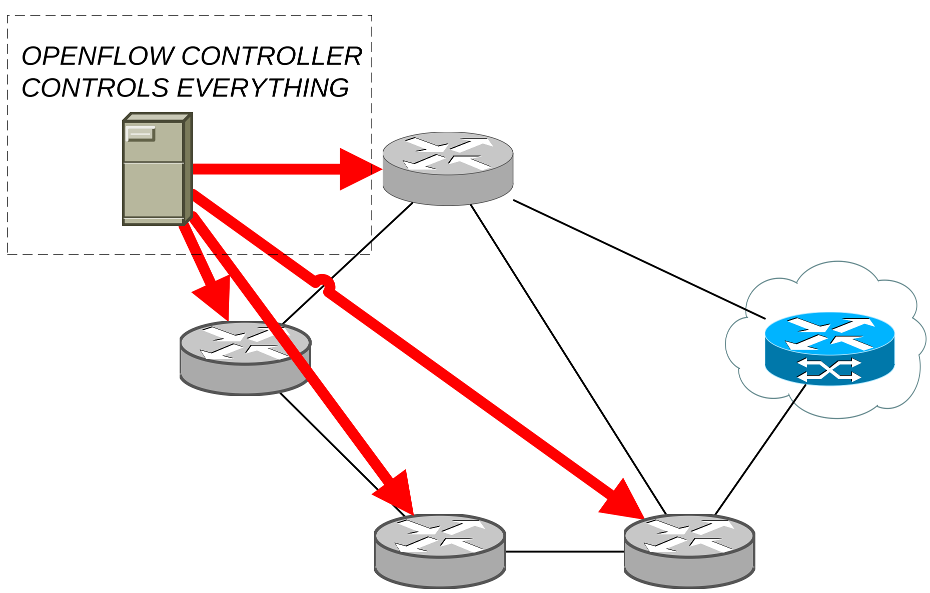


c. **Hybrid**: This model is very similar to the augmented model except that controller-originated policy can be imposed anywhere in the network. This gives additional granularity to network administrators; the main benefit over the augmented model is that the hybrid model is always topology-independent. The controller can overwrite the forward table of any device which means that topological restrictions are removed. Cisco's Application Centric Infrastructure (ACI) is a good example of this model. ACI separates reachability from policy, which is critical from both survivability and scalability perspectives. The failure of the centralized control in these models has an identical effect to that of a controller in the augment model; the network falls back to a distributed control-plane model. The impact of a failed controller is a little more significant since more devices are affected by the controller's policy. A diagram is shown below.



d. **Centralized**: This is the model most commonly referenced when the phrase "SDN" is spoken. It relies on a single controller, which hosts the entire control-plane. Ultimately, this device commands all of the devices in the forwarding-plane. This controllers writes their forwarding tables with the proper information (which doesn't necessarily have to be an IP-based table, it could be anything) as specified by the administrators. This offers very granular control, in many cases, of individual flows in the network. The hardware forwarders can be commoditized into white boxes (or branded white boxes, sometimes called brite boxes) which are often inexpensive. Another value proposition of centralizing the control-plane is that a "device" can be almost anything: router, switch, firewall, load-balancer, etc. Emulating software functions on generic hardware platforms can add flexibility to the business.

   The most significant drawback is the newly-introduced single point of failure and the inability to create failure domains as a result. Some SDN scaling architectures suggest simply adding additional controllers for fault tolerance or to create a hierarchy of controllers for larger networks. While this is a valid technique, it somewhat invalidates the "centralized" model because with multiple controllers, the distributed control-plane is reborn. The controllers still must synchronize their routing information using some network-based protocol and the possibility of inconsistencies between the controllers is real. When using this multi-controller architecture, the network designer must understand that there is, in fact, a distributed control-plane in the network; it has just been moved around. The failure of all controllers means the entire failure domain supported by those controllers will be inoperable. The failure of the communication paths between controllers could likewise cause inconsistent/intermittent problems with forward, just like a fully distributed control-plane. OpenFlow is a good example of a fully-centralized model and an example of this architecture is shown below.



2.1 Describe functional elements of network programmability (SDN) and how they interact

2.1.1 Controllers

As discussed briefly above, “controllers” are components that are responsible for programming forwarding tables of data-plane device. Controllers themselves could even be routers, like Cisco’s PfR operating as a master controller (MC), or they could be software-only appliances, as seen with OpenFlow networks or Cisco’s Application Policy Infrastructure Controller (APIC) used with ACI. The models discussed above help detail the significance of the controller; this is entirely dependent on the deployment model. The more involved a controller is, the more flexibility the network administrator gains. This must be weighed against the increased reliance on the controller itself.

2.1.2 APIs

An Application Program Interface (API) is meant to define a standard way of interfacing with a software application or operating system. It may consistent of functions (methods, routines, etc), protocols, system call constructors, and other “hooks” for integration. Both the controllers and business applications would need the appropriate APIs revealed for integration between the two. This makes up the northbound communication path as discussed in section 2.1.5. By creating a common API for communications between controllers and business applications, either one can be changed at any time without significantly impacting the overall architecture.

A common API that is discussed within the networking world is Representational State Transfer (REST). REST represents an “architectural style” of transferring information between clients and servers. In essence, it is a way of defining attributes or characteristics of how data is moved. REST is commonly used with HTTP by combining traditional HTTP methods (GET, POST, PUT, DELETE, etc) and Universal Resource Identifiers (URI). The end result is that API requests look like URIs and are used to fetch/write specific pieces of data to a target machine. This simplification helps promote automation, especially for web-based applications or services. Note that HTTP is stateless which means the server does not store session information for individual flows; REST API calls retain this stateless functionality as well. This allows for seamless REST operation across HTTP proxies and gateways.

2.1.3 Scripting

Scripting is a fundamental topic of an effective automation design. Scripting can allow network administrators to define the policy constraints for a given application in a manner than is consistent and clear. Other operators can “fork” this script (copy it and start a new version from a common point) and potentially “merge” the changes back in later. This is how advanced policies can be defined in an SDN-based architecture. The scripts can be manually applied as discussed earlier with the VLAN-creation example, or they could be assembled in sequence by an orchestrator as part of a larger workflow or process. In any case, an administrator needs to write the script in the first place, and like all pieces of code, it must be maintained, tested, versioned, and continuously monitored. A popular repository for text file configuration management is Github or BitBucket, while popular scripting languages include Python, Ruby, JavaScript, and Perl. Neither of these are complete lists.

2.1.4 Agents

Management agents are typically on-box software components that allow an infrastructure device to report traffic conditions back to the controller. This information flows upstream through the southbound interface discussed in section 2.1.5 and is primarily used to “complete” the controller’s view of the network. Given this information, the controller can sense congestion, route around failures, and perform all manner of fancy traffic-engineering as required by the business applications. Many of these agents perform the same general function as SNMP yet offer increased flexibility and granularity as they are programmable.

Agents could also be used for non-management purposes, at least from a general view. Interface to the Routing System (I2RS) is an SDN technique where a specific control-plane agent is required on every data-plane forwarder. This agent is effectively the control-plane client that communicates upstream towards the controller. This is the channel by which the controller consults its RIB and populates the FIB of the forwarding devices. The same is true for OpenFlow (OF) which is a fully centralized SDN model. The agent can be considered an interface to a data-plane forwarder for a control-plane SDN controller. A simple categorization method is to quantify management strategies as “agent based” or “agent-less based”. Agent is pull-based, which means the agent connects with master. Changes made on master are pulled down when agent is “ready”. This can be significant since if a network device is currently tolerating a microburst, the management agent can wait until the contention abates before passing telemetry data to the master. Agent-less is push-based like SNMP traps, where the triggering of an event on a network device creates a message for the controller in unsolicited fashion. The other direction also true; a master can use SSH to access a device for programming whenever the master is “ready”.

Although not specific to “agents”, there are several common applications/frameworks that are used for device management. Some of them rely on agents while others do not. Three of them are discussed briefly below as these are found in Cisco’s *“NX-OS DevNet Network Automation Guide”.* Note that subsets of the exact definitions are added here. Since these are third-party products, the author does not want to misrepresent the facts or capabilities as understood by Cisco.

a. **Puppet (by Puppet Labs):** *The Puppet software package is an open source automation toolset for managing servers and other resources by enforcing device states, such as configuration settings. Puppet components include a puppet agent which runs on the managed device (client) and a puppet master (server) that typically runs on a separate dedicated server and serves multiple devices. The Puppet master compiles and sends a configuration manifest to the agent. The agent reconciles this manifest with the current state of the node and updates state based on differences. A puppet manifest is a collection of property definitions for setting the state on the device. Manifests are commonly used for defining configuration settings, but they can also be used to install software packages, copy files, and start services.*

   In summary, Puppet is agent-based (requiring software installed on the client) and pushes complex data structures to managed nodes from the master server. Puppet manifests are used as data structures to track node state and display this state to the network operators.

b. **Chef (by Chef Software):** *Chef is a systems and cloud infrastructure automation framework that deploys servers and applications to any physical, virtual, or cloud location, no matter the size of the infrastructure. Each organization is comprised of one or more workstations, a single server, and every node that will be configured and maintained by the chef-client. A cookbook defines a scenario and contains everything that is required to support that scenario, including libraries, recipes, files, and more. A Chef recipe is a collection of property definitions for setting state on the device. While recipes are commonly used for defining configuration settings, they can also be used to install software packages, copy files, start services, and more.*

   In summary, Chef is very similar to Puppet in that it requires agents and manages devices using complex data structures. The concepts of cookbooks and recipes are specific to Chef (hence the name) which contribute to a hierarchical data structure management system. A Chef cookbook is loosely equivalent to a Puppet manifest.

c. **Ansible (by Red Hat):** *Ansible is an open source IT configuration management and automation tool. Unlike Puppet and Chef, Ansible is agent-less, and does not require a software agent to be installed on the target node (server or switch) in order to automate the device. By default, Ansible requires SSH and Python support on the target node, but Ansible can also be easily extended to use any API.*

   In summary, Ansible is somewhat lighter-weight than Puppet or Chef given that management is agent-less. No custom software needs to be installed on any device provided that it supports SSH. This can be a drawback since individual device CLIs must be exposed to network operators (or, at best, the Ansible automation engine) instead of using a more abstract API design.

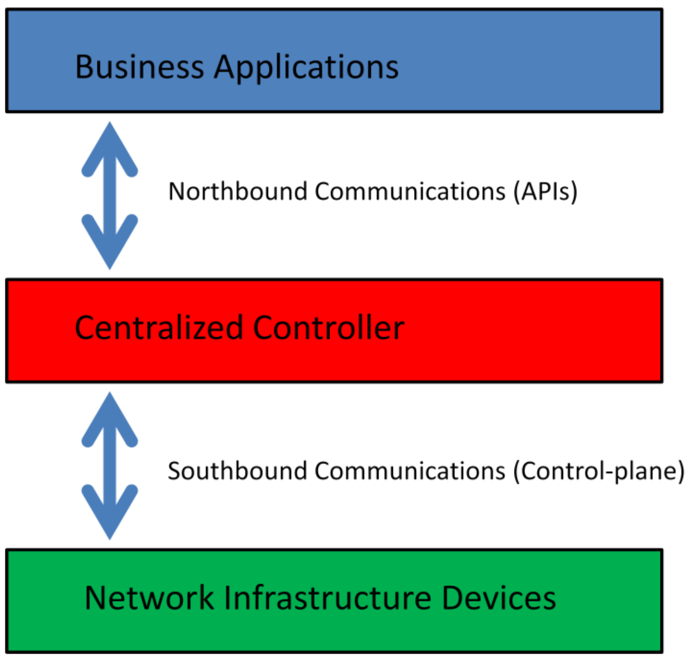
2.1.5 Northbound vs. Southbound protocols

Controllers sit "in the middle" of the SDN notional architecture. It uses northbound and southbound communication paths to operate with other components of the architecture.

The northbound interfaces are considered APIs which are interfaces to existing business applications. This is generally used so that applications can make requests of the network, which could include specific performance requirements (bandwidth, latency, etc). Because the controller "knows" this information by communicating with the infrastructure devices via management agents, it can determine the best paths through the network to satisfy these constraints. This is loosely analogous to the original intent of the Integrated Services QoS model using Resource Reservation Protocol (RSVP) where applications would reserve bandwidth on a per-flow basis. It is also similar to MPLS TE constrained SPF (CSPF) where a single device can source-route traffic through the network given a set of requirements. The logic is being extended to applications with a controller "shim" in between, ultimately providing a full network view for optimal routing. A REST API is an example of a northbound interface.

The southbound interfaces include the control-plane protocol between the centralized controller and the network forwarding hardware. These are the less intelligent network devices used for forwarding only (assuming a centralized model). A common control-plane used for this purpose would be OpenFlow; the controller determines the forwarding tables per flow per network device, programs this information, and then the devices obey it. Note that OpenFlow is not synonymous with SDN; it is just an example of one southbound control-plane protocol. Because the SDN controller is sandwiched between the northbound and southbound interfaces, it can be considered "middleware" in a sense. The controller is effectively able to evaluate application constraints and produce forwarding-table outputs.

The image below depicts a very high-level diagram of the SDN layers as it relates to interaction between components.



2.2 Describe aspects of virtualization and automation in network environments

Network virtualization is often misunderstood as being something as simple as "virtualize this server using a hypervisor and extend some VLANs to the host". Network virtualization is really referring to the creation of virtual topologies using a variety of technologies to achieve a given business goal. Sometimes these virtual topologies are overlays, sometimes they are forms of multiplexing, and sometimes they are a combination of the two. Here are some common examples (not a complete list) of network virtualization using well-known technologies.

a. **Ethernet VLANs using 802.1q encapsulation**. Often used to create virtual networks at layer 2 for security segmentation, traffic hair pinning through a service chain, etc. This is a form of data multiplexing over Ethernet links. It isn't a tunnel/overlay since the layer 2 reachability information (MAC address) remains exposed and used for forwarding decisions.

b. **VPN Routing and Forwarding (VRF) tables or other layer-3 virtualization techniques**. Similar uses as VLANs except virtualizes an entire routing instance, and is often used to solve a similar set of problems. Can be combined with VLANs to provide a complete virtual network between layers 2 and 3. Can be coupled with GRE for longer-range virtualization solutions over a core network that may or may not have any kind of virtualization. This is a multiplexing technique as well but is control-plane only since there is no change to the packets on the wire, nor is there any inherent encapsulation (not an overlay).
c. **Frame Relay DLCI encapsulation**. Like a VLAN, creates segmentation at layer 2 which might be useful for last-mile access circuits between PE and CE for service multiplexing. The same is true for Ethernet VLANs when using EV services such as EV-LINE, EV-LAN, and EV-TREE. This is a data-plane multiplexing technique specific to frame relay.
d. **MPLS VPNs**. Different VPN customers, whether at layer 2 or layer 3, are kept completely isolated by being placed in a different virtual overlay across a common core that has no/little native virtualization. This is an example of an overlay type of virtual network.
e. **VXLAN**. Just like MPLS VPNs; creates virtual overlays atop a potentially non-virtualized core. Doesn't provide a native control-plane, but that doesn't matter; it's still a virtualization technique. Could be paired with BGP EVPN if MAC routing is desired. This is another example of an overlay type of virtual network.
f. **OTV**. Just like MPLS VPNs; creates virtual overlays atop a potentially non-virtualized core, except provides a control-plane for MAC routing. IP multicast traffic is also routed intelligently using GRE encapsulation with multicast destination addresses. This is another example of an overlay type of virtual network.

2.2.1 DevOps methodologies, tools and workflows

The term "DevOps" is relatively new and is meant to describe not just a job title but a cultural shift in service delivery, management, and operation. It was formerly known as "agile system administration" or "agile methodology". The keyword "agile" typically refers to the integration of development and operations staff throughout the entire lifecycle of a service. The idea is to tear down the silos and the resulting poor service delivery that both teams facilitate. Often times, developers will create applications without understanding the constraints of the network, while the network team will create a network (ineffective QoS, slow rerouting, etc) policies that don't support the business-critical applications.

The tools and workflows used within the DevOps community are things that support an information sharing environment. Many of them are focused on version control, service monitoring, configuration management, orchestration, containerization, and everything else needed to typically support a service through its lifecycle. The key to DevOps is that using a specific DevOps "tool" does not mean an organization has embraced the DevOps culture or mentality. A good phrase is "People over Process over Tools", as the importance of a successful DevOps team is reliance on those things, in that order. DevOps also introduces several new concepts. Two critical ones are continuous integration (CI) and continuous delivery (CD). The CI/CD mindset suggests several changes to traditional SW development. Some of the key points are listed below.

a. Everyone can see the changes: Dev, Ops, Quality Assurance (QA), management, etc
b. Verification is an exact clone of the production environment, not simply a smoke-test on a developer's test bed
c. The build and deployment/upgrade process is automated
d. Provide SW in short timeframes and ensure releases are always available in increments
e. Reduce friction, increase velocity
f. Reduce silos, increase collaboration

On the topic of SW development models, it can be beneficial to compare the commonly used models with the new "agile" or DevOps mentality. Additional details on these software development models can be found in the references. Below is a comparison chart of the different software development models.

	Waterfall	**Iterative**	**Agile**
Basic Description	Five serial phases: 1. Requirements 2. Design 3. Implementation 4. Verification 5. Maintenance Not much room for feedback	Like the waterfall model, but operates in loops. This creates a feedback mechanism at each cycle to promote a faster and more flexible process.	Advances when the current step/function/feature is complete; cyclical model.
Pros	Simple, well understood, long history, requires minimal resources / management oversight	Simple, well understood, opportunity to adjust, requires slightly more resources than waterfall (but still reasonable)	Customer is engaged (better feedback), early detection of issues during rapid code development periods (sprints)
Cons	Difficult to revert, customer is not engaged until the end, higher risk, slow to deliver	Can be inefficient, customer feedback comes at the end of an iteration (not within)	High quantity of resources required, more focused management/customer interaction team needed

2.2.2 Network/application function virtualization (NFV, AFV)

NFV and AFV refer to taking specific network functions, virtualizing them, and assembling them in a sequence to meet a specific business need. NFV and AFV by themselves, in isolation, are generally synonymous with creating virtual instances of things which were once physical. Many vendors offer virtual routers (Cisco CSR1000v, Cisco IOS-XR9000v, etc), security appliances (Cisco ASAv, Cisco NGIPSv, etc), telephony and collaboration components (Cisco UCM, CUC, IM&P, UCCX, etc) and many other things that were once physical appliances. Separating these things into virtual functions allows a wide variety of organizations, from cloud providers to small enterprises, to select only the components they require. The following chapter describes a commonly used and powerful NFV/AFV use case.

2.2.3 Service function chaining

As mentioned briefly above, service chaining is taking NFV/AFV components and sequencing them to create some customized “chain of events” to solve a business problem. NFV/AFV by itself isn’t terribly useful if specific services cannot be easily linked in a meaningful way. Service chaining, especially in cloud environments, can be achieved in a variety of technical ways. For example, one organization may require routing and firewall, while another may require routing and intrusion prevention. The per-customer granularity is a powerful offering of service chaining in general. The main takeaway is that all of these solutions are network virtualization solutions of sorts.

a. **MPLS and Segment Routing**. Some headend LSR needs to impose different MPLS labels for each service in the chain that must be visited to provide a given service. MPLS is a natural choice here given the label stacking capabilities and theoretically-unlimited label stack depth.
b. **Networking Services Header (NSH).** Similar to the MPLS option except is purpose-built for service chaining. Being purpose-built, NSH can be extended or modified in the future to better support new service chaining requirements, where doing so with MPLS shim header formats is less likely. MPLS would need additional headers or other ways to carry “more” information.
c. **Out of band centralized forwarding**. Although it seems unmanageable, a centralized controller could simply instruct the data-plane devices to forward certain traffic through the proper services without any in-band encapsulation being added to the flow. This would result in an explosion of core state which could limit scalability, similar to policy-based routing at each hop.
d. **Cisco vPath**: This is a Cisco innovation that is included with the Cisco Nexus 1000v series switch for use as a distributed virtual switch (DVS) in virtualized server environments. Each service is known as a virtual service node (VSN) and the administrator can select the sequence in which each node should be transited in the forwarding path. Traffic transiting the Nexus 1000v switch is subject to redirection using some kind of overlay/encapsulation technology. Specifically, MAC-in-MAC encapsulation is used for layer-2 tunnels while MAC-in-UDP is used for layer-4 tunnels.

2.2.4 Performance, availability, and scaling considerations

There are many trade-offs between the different SDN models. The following page includes a table that attempts to capture the most important ones.

	Distributed	Augmented	Hybrid	Centralized
Availability	Dependent on the protocol convergence times and redundancy in the network	Dependent on the protocol convergence times and redundancy in the network. Doesn't matter how bad the SDN controller is … its failure is tolerable	Dependent on the protocol convergence times and redundancy in the network. Doesn't matter how bad the SDN controller is … its failure is tolerable	Heavily reliant on a single SDN controller, unless one adds controllers to split failure domains or to create resilience within a single failure domain (which introduces a distributed control-plane in both cases)
Granularity / control	Generally low for IGPs but better for BGP. All devices generally need a common view of the network to prevent loops independently. MPLS TE helps somewhat.	Better than distributed since policy injection can happen at the network edge, or a small set of nodes. Can be combined with MPLS TE for more granular selection.	Moderately granular since SDN policy decisions are extended to all nodes. Can influence decisions based on any arbitrary information with a datagram	Very highly granular; complete control over all routing decisions based on any arbitrary information with a datagram
Scalability (assume flow-based policy and state retention)	Very high in a properly designed network (failure domain isolation, topology summarization, reachability aggregation, etc)	High, but gets worse with more policy injection. Policies are generally limited to key nodes (such as border routers)	Moderate, but gets worse with more policy injection. Policy is proliferated across the network to all nodes (though the exact quantity may vary per node)	Depends; all devices retain state for all transiting flows. Hardware-dependent on TCAM and whether SDN can use other tables such as L4 information, IPv6 flow labels, etc

2.3 Resources and References

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https://developer.cisco.com/site/devnet/home/index.gsp
www.cisco.com/go/sdn
BRKNMS-2446 - Do IT with DevOps (2015 San Diego)
BRKDEV-2001 - DevOps in Programmable Network Environments (2015 San Diego)
BRKCRT-2603 - Cloudy with a chance of SDN (2015 San Diego)
BRKSDN-2761 - OpenDaylight: The Open Source SDN Controller Platform (2015 San Diego)
BRKSDN-1903 - A Model-driven Approach to Software Defined Networks with Yang, Netconf/Restconf (2015 San Diego)
BRKRST-1014: Introduction to Software-Defined Networking (SDN) and Network Programmability (2015 San Diego)
Cisco - Introducing Network Programmability Fundamentals
Cisco - Introduction to APIC EM Deployment
Introduction to SDN (LiveLesson)
ETSI NFV Whitepaper
NX-OS DevNet Network Automation Guide
RFC6241 - NETCONF
RFC6020 - YANG

3. Internet of Things (IoT)

IoT, sometimes called Internet of Everything (IoE), is a concept that many non-person entities (NPEs) or formerly non-networked devices in the world would suddenly be networked. This typically includes things like window blinds, light bulbs, water treatment plant sensors, home heating/cooling units, street lights, and anything else that could be remotely controlled or monitored. The business drivers for IoT are substantial: electrical devices (like lights and heaters) could consume less energy by being smartly adjusted based on changing conditions, window blinds can open and close based on the luminosity of a room, and chemical levels can be adjusted in a water treatment plant by networked sensors. These are all real-life applications of IoT and network automation in general.

The term Low-power and Lossy Networks (LLN) is commonly used in the IoT space since it describes the vast majority of IoT networks. LLNs have the following basic characteristics (incomplete list):

a. Bandwidth constraints
b. Highly unreliable
c. Limited resources (power, CPU, and memory)
d. Extremely high scale (hundreds of millions and possibly more)

3.1 Describe architectural framework and deployment considerations

IoT combines a number of emerging technologies into its generalized network architecture. The architecture consists primarily of four layers:

a. **Data center (DC) Cloud**: Although not a strict requirement, the understanding that a public cloud infrastructure exists to support IoT is a common one. A light bulb manufacturer could partner with a networking vendor to develop network-addressable light bulbs which are managed from a custom application running in the public cloud. This might be better than a private cloud solution since, if the application is distributed, regionalized instances could be deployed in geographically dispersed areas using an "anycast" design for scalability and performance improvements. As such, public cloud is generally assumed to be the DC presence for IoT networks.

b. **Core Networking and Services**: This could be a number of transports to connect the public cloud to the sensors. The same is true for any connection to public cloud, in reality, since even businesses need to consider the manner in which they connect to public cloud. The primary three options (private WAN, IXP, or Internet VPN) were discussed in the Cloud section. The same options apply here. A common set of technologies/services seen within this layer include IP, MPLS, mobile packet core, QoS, multicast, security, network services, hosted cloud applications, big data, and centralized device management (such as a network operations facility).

c. **Multi-service Edge (access network)**: Like most SP networks, the access technologies tend to vary greatly based on geography, cost, and other factors. Access networks can be optically-based to provide Ethernet handoffs to IoT devices; this would make sense for relatively large devices that would have Ethernet ports and would be generally immobile. Mobile devices, or those that are small or remote, might use cellular technologies such as 2G, 3G, or 4G/LTE for wireless backhaul to the closest POP. A combination of the two could be used by extending Ethernet to a site and using 802.11 WIFI to connect the sensors to the WLAN. The edge network may require use of "gateways" as a short-term solution for bridging (potentially non-IP) IoT networks into traditional IP networks. The gateways come with an associated high CAPEX and OPEX since they are custom devices to solve a very specific use-case. Specifically, gateways are designed to perform some subset of the following functions, according to Cisco:

   I. *Map semantics between two heterogeneous domains:* The word semantics in this context refers to the way in which two separate networks operate and how each network interprets things. If the embedded systems network is a transparent radio mesh using a non-standard set of protocols while the multi-service edge uses IP over cellular, the gateway is responsible for "presenting" common interfaces to both networks. This allows devices in both networks to communicate using a "language" that is common to each.
   II. *Perform translation in terms of routing, QoS security, management, etc:* These items are some concrete examples of semantics. An appropriate analogy for IP networkers is stateless NAT64; an inside-local IPv4 host must send traffic to some outside-local IPv4 address which represents an outside-global IPv6 address. The source of that packet becomes an IPv6 inside-global address so that the IPv6 destination can properly reply.
   III. *Do more than just protocol changes:* The gateways serve as interworking devices between architectures at an architectural level. The gateways might have a mechanism for presenting network status/health between layers, and more importantly, be able to

fulfill their architectural role in ensuring end-to-end connectivity across disparate network types.

Embedded Systems (Smart Things Network): This layer represents the host devices themselves. They can be wired or wireless, smart or less smart, or any other classification that is useful to categorize an IoT component. Often times, such devices support zero-touch provisioning (ZTP) which helps with the initial deployment of massive-scale IoT deployments. For static components, these components are literally embedded in the infrastructure and should be introduced during the construction of a building, factory, hospital, etc. These networks are rather *stochastic* (meaning that behavior can be unpredictable). The author classifies wireless devices into three general categories which help explain what kind of RF-level transmission methods are most sensible:

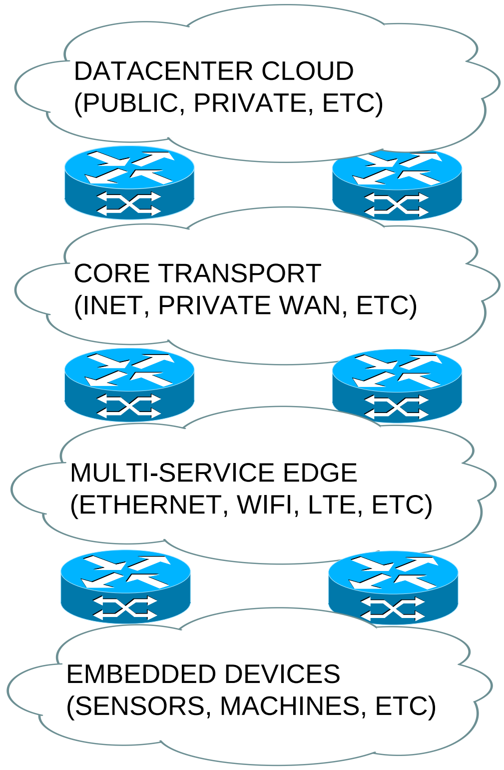
I. **Long range**: Some devices may be placed very far from their RF base stations/access points and could potentially be highly mobile. Smart automobiles are a good example of this; such devices are often equipped with cellular radios, such as 4G/LTE. Such an option is not optimal for supporting LLNs given the cost of radios and power required to run them. To operate a private cellular network, the RF bands must be licensed (in the USA, at least), which creates an expensive and difficult barrier for entry.

II. **Short range with "better" performance:** Devices that are within a local area, such as a building, floor of a large building, or courtyard area, could potentially use unlicensed frequency bands while transmitting at low power. These devices could be CCTV sensors, user devices (phones, tablets, laptops, etc), and other general-purpose things whereby maximum battery life and cost savings are eclipsed by the need for superior performance. IEEE 802.11 WIFI is commonly used in such environments. IEEE 802.16 WIMAX specifications could also be used, but in the author's experience, it is rare.

III. **Short range with "worse" performance:** Many IoT devices fall into this final category whereby the device itself has a very small set of tasks it must perform, such as sending a small burst of data when an event occurs (i.e., some nondescript sensor). Devices are expected to be installed one time, rarely maintained, procured/operated at low cost, and be value-engineered to do very few things. These devices are less commonly deployed in home environments since many homes have WIFI; they are more commonly seen spread across cities. Examples might include street lights, sprinklers, and parking/ticketing meters. IEEE has defined 802.15.4 to support low-rate wireless personal area networks (LR-PANS) which is used for many such IoT devices. Note that 802.15.4 is the foundation for upper-layer protocols such as ZigBee and WirelessHART. ZigBee, for example, is becoming popular in homes to network some IoT devices, such as thermostats, which may not support WIFI in their hardware.

IEEE 802.15.4 is worth a brief discussion by itself. Unlike WIFI, all nodes are "full-function" and can act as both hosts and routers; this is typical for mesh technologies. A device called a PAN coordinator is analogous to a WIFI access point (WAP) which connects the PAN to the wired infrastructure; this technically qualities the PAN coordinator as a "gateway" discussed earlier.

The basic IoT architecture is depicted below.



As a general comment, one IoT strategy is to "mesh under" and "route over". This loosely follows the 7-layer OSI model by attempting to constrain layers 1-2 to the IoT network, to include RF networking and link-layer communications, then using some kind of IP overlay of sorts for network reachability. Additional details about routing protocols for IoT are discussed later in this document.

3.1.1 Performance, reliability and scalability

The performance of IoT devices is going to be a result of the desired security and the access type. Many IoT devices will be equipped with relatively inexpensive and weak hardware; this is sensible from a business perspective as the device only needs to perform a few basic functions. This could be seen a compromise of security since strong ciphers typically require more computational power for encryption/decryption functionality. In addition, some IoT devices may be expected to last for decades while it is highly unlikely that the same is true about cryptographic ciphers. In short, more expensive hardware is going to be more secure and resilient.

The access type is mostly significant when performance is discussed. Although 4G LTE is very popular and widespread in the United States and other countries, it is not available everywhere. Some parts of the world are still heavily reliant on 2G/3G cellular service which is less capable and slower. A widely distributed IoT network may have a combination of these access types with various levels of performance. Higher performing 802.11 WIFI speeds typically require more expensive radio hardware, more electricity, and a larger physical size. Physical access types (wired devices) will be generally immobilized which could be considered a detriment to physical performance, if mobility is required for an IoT device to do its job effectively.

3.1.2 Mobility

The mobility of an IoT device is going to be largely determined by its access method. Devices that are on 802.11 WIFI within a factory will likely have mobility through the entire factory, or possibly the entire complex, but will not be able to travel large geographic distances. For some specific manufacturing work carts (containing tools, diagnostic measurement machines, etc), this might be an appropriate method. Devices connected via 4G LTE will have greater mobility but will likely represent something that isn't supposed to be constrained to the factory, such as a service truck or van. Heavy machinery bolted to the factory floor might be wired since it is immobile.

3.1.3 Security and privacy

Providing security and private for IoT devices is challenging mostly due to the sheer expanse of the access network and supported clients (IoT devices). Similar concepts still apply as they would for normal hosts except for needing to work in a massively scalable and distributed network:

a. Use IEEE 802.1x for wired and wireless authentication for all devices. This is normally tied into a Network Access Control (NAC) architecture which authorizes a set of permissions per device.
b. Encrypt wired and wireless traffic using MACsec/IPsec as appropriate.
c. Maintain physical accounting of all devices, especially small ones, to prevent theft and reverse engineering.
d. Do not allow unauthorized access to sensors; ensure remote locations are secure also.
e. Provide malware protection for sensors so that the compromise of a single sensor is detected quickly and suppressed.
f. Rely on cloud-based threat analysis (again, assumes cloud is used) rather than a distributed model given the size of the IoT access network and device footprint. Sometimes this extension of the cloud is called the "fog" and encompasses other things that product and act on IOT data.

Another discussion point on the topic of security is determining how/where to "connect" an IoT network. This is going to be determined based on the business need, as always, but the general logic is similar to what traditional corporate WANs use:

a. **Fully private connections:** Some IoT networks have no legitimate need to be accessible via the public Internet. Such examples would include Government sensor networks which may be deployed in a battlefield support capacity. More common examples might include Cisco's "Smart Grid" architecture which is used for electricity distribution and management within a city. Exposing such a critical resource to a highly insecure network offers little value since the public works department can likely control it from a dedicated NOC. System updates can be performed in-house and the existence of the IoT network can be (and often times, should be) largely unknown by the general population. In general, IoT networks that fall into this category are "producer-oriented" networks.

b. **Public Internet:** Other IoT networks are designed to have their information shared or made public between users. One example might be a managed thermostat service; users can log into a web portal hosted by the service provider to check their home heating/cooling statistics, make changes, pay bills, request refunds, submit service tickets, and the like. Other networks might be specifically targeted to sharing information publicly, such as fitness watches that track how long an individual exercises. The information could be posted publicly and linked to one's social media page so others can see it. A more practical and useful example could include *public safety information via a web portal* hosted by the Government. In general, IoT networks that fall into this category are "consumed-oriented" networks.

3.1.4 Standards and compliance

Controlling access and identifying areas of responsibility can be challenging with IoT. Cisco provides the following example: *For example, Smart Traffic Lights where there are several interested parties such as Emergency Services (User), Municipality (owner), Manufacturer (Vendor). Who has provisioning access? Who accepts Liability?*

There is more than meets the eye with respect to standards and compliance for street lights. Most municipalities (such as counties or townships within the United States) have ordinances that dictate how street lighting works. The light must be a certain color, must not "trespass" into adjacent streets, must not negatively affect homeowners on that street, etc. This complicates the question above because the lines become blurred between organizations rather quickly. In cases like this, the discussions must occur between all stakeholders, generally chaired by a Government/company representative (depending on the consumer/customer), to draw clear boundaries between responsibilities.

Radio frequency (RF) spectrum is a critical point as well. While WIFI can operate in the 2.4 GHz and 5.0 GHz bands without a license, there are no unlicensed 4G LTE bands at the time of this writing. Deploying 4G LTE capable devices on an existing carrier's network within a developed country may not be a problem. Doing so in developing or undeveloped countries, especially if 4G LTE spectrum is tightly regulated but poorly accessible, can be a challenge.

Several new protocols have been introduced specifically for IoT, some of which are standardized:

a. **RPL - IPv6 Routing Protocol for LLNs (RFC 6550):** RPL is a distance-vector routing protocol specifically designed to support IoT. At a high-level, RPL is a combination of control-plane and forwarding logic of three other technologies: regular IP routing, multi-topology routing (MTR), and MPLS traffic-engineering (MPLS TE). RPL is similar to regular IP routing in that directed acyclic graphs (DAG) are created through the network. This is a fancy way of saying "loop-free shortest path" between two points. These DAGs can be "colored" into different topologies which represent different network characteristics, such as high bandwidth or low latency. This forwarding paradigm is similar to MTR in concept. Last, traffic can be assigned to a colored DAG based on administratively-defined constraints, including node state, node energy, hop count, throughput, latency, reliability, and color (administrative preference). This is similar to MPLS TE's constrained shortest path first (CSPF) process which is used for defining administrator-defined paths through a network based on a set of constraints, which might have technical and/or business drivers behind them.

b. **6LoWPAN - IPv6 over Low Power WPANs (RFC 4919):** This technology was specifically developed to be an *adaptation layer for IPv6 for IEEE 802.15.4* wireless networks. Specifically, it "adapts" IPv6 to work over LLNs which encompasses many functions:

   I. **MTU correction:** The minimum MTU for IPv6 across a link, as defined in RFC2460, is 1280 bytes. The maximum MTU for IEEE 802.15.4 networks is 127 bytes. Clearly, no value can mathematically satisfy both conditions concurrently. 6LoWPAN performs fragmentation and reassembly by breaking the large IPv6 packets into IEEE 802.15.4 frames for transmission across the wireless network.

   II. **Header compression:** Many compression techniques are stateful and CPU-hungry. This strategy would not be appropriate for low-cost LLNs, so 6LoWPAN utilizes an algorithmic (stateless) mechanism. RFC4944 defines some common assumptions:

      i. The version is always IPv6.
      ii. Both source and destination addresses are link-local.
      iii. The low-order 64-bits of the link-local addresses can be derived from the layer-2 network addressing in an IEEE 802.15.4 wireless network.
      iv. The packet length can be derived from the layer-2 header.
      v. Next header is always ICMP, TCP, or UDP.
      vi. Flow label and traffic class are always zero.

   As an example, an IPv6 header (40 bytes) and a UDP header (8 bytes) are 48 bytes long when concatenated. This can be compressed down to 7 bytes by 6LoWPAN.

   III. **Mesh routing:** Somewhat similar to WIFI, mesh networking is possible, but requires up to 4 unique addresses. The original source/destination addresses can be retained in a new "mesh header" while the per-hop source/destination addresses are written to the MAC header.

   IV. **MAC level retransmissions:** IP was designed to be fully stateless and any retransmission or flow control was the responsibility of upper-layer protocols, such as TCP. When using 6LoWPAN, retransmissions can occur at layer-2.

c. **CoAP - Constrained Application Protocol (RFC7252):** At a high-level, CoAP is very similar to HTTP in terms of the capabilities it provides. It is used to support the transfer of application data using common methods such as GET, POST, PUT, and DELETE. CoAP runs over UDP port 5683 by default (5684 for secure CoAP) and was specifically designed to be lighter weight and faster than HTTP. Like the other IoT protocols, CoAP is designed for LLNs, and more specifically, to support machine-to-machine communications. CoAP has a number of useful features and characteristics:

   I. **Supports multicast:** Because it is UDP-based, IP multicast is possible. This can be used both for application discovery (in lieu of DNS) or efficient data transfer.

II. **Built-in security:** CoAP supports using datagram TLS (DTLS) with both pre-shared key and digital certificate support. As mentioned earlier, CoAP DTLS uses UDP port 5684.
III. **Small header:** The CoAP overhead adds only 4 bytes.
IV. **Fast response:** When a client sends a CoAP GET to a server, the requested data is immediately returned in an ACK message, which is the fastest possible data exchange.

Despite CoAP being designed for maximum efficiency, it is not a general replacement for HTTP. It only supports a subset of HTTP capabilities and should only be used within IoT environments. To interwork with HTTP, one can deploy an HTTP/CoAP proxy as a “gateway” device between the multi-service edge and smart device networks.

d. **Message Queuing Telemetry Transport (not standardized):** MQTT is, in a sense, the predecessor of CoAP in that it was created in 1999 and was specifically designed for lightweight, web-based, machine-to-machine communications. Like HTTP, it relies on TCP, except uses ports 1883 and 8883 for plain-text and TLS communications, respectively. Being based on TCP also implies a client/server model, similar to HTTP, but not necessary like CoAP. Compared to CoAP, MQTT is losing traction given the additional benefits specific to modern IoT networks that CoAP offers.

The table below briefly compares CoAP, MQTT, and HTTP.

	CoAP	**MQTT**	**HTTP**
Transport and ports	UDP 5683/5684	TCP 1883/1889	TCP 80/443
Security support	DTLS via PSK/PKI	TLS via PSK/PKI	TLS via PSK/PKI
Multicast support	Yes, but no encryption support yet	No	No
Lightweight	Yes	Yes	No
Standardized	Yes	No; in progress	Yes
Rich feature set	No	No	Yes

3.1.5 Migration

Migrating to IoT need not be swift. For example, consider an organization which is currently running a virtual private cloud infrastructure with some critical in-house applications in their private cloud. All remaining COTS applications are in the public cloud. Assume this public cloud is hosted locally by an ISP and is connected via an MPLS L3VPN extranet into the corporate VPN. If this corporation owns a large manufacturing company and wants to begin deploying various IoT components, it can begin with the large and immobile pieces.

The multi-service edge (access) network from the regional SP POP to the factory likely already supports Ethernet as an access technology, so devices can use that for connectivity. Over time, a corporate WLAN can be extended for 802.11 WIFI capable devices. Assuming this organization is not deploying a private 4G LTE network, sensors can immediately be added using cellular as well. The migration strategy towards IoT is very similar to adding new remote branch sites, except the number of hosts could be very large. The LAN, be it wired or wireless, still must be designed correctly to support all of the devices.

3.1.6 Environmental impacts on the network

Environment impacts are especially important for IoT given the scale of devices deployed. Although wireless technologies become more resilient over time, they remain susceptible to interference and other natural phenomena which can degrade network connectivity. Some wireless technologies are even impacted by rain, a common occurrence in many parts of the word. The significance of this with IoT is to consider when to use wired or wireless communication as for a sensor. Some sensors may even be able to support multiple communications styles in an active/standby method. As is true in most networks, resilient design is important in ensuring that IoT-capable devices are operable.

3.2 Resources and References

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RFC6550 - RPL
RFC4919 - 6LoWPAN
RFC7252 - CoAP
MQTT Website