VIRTUAL PRIVATE NETWORKS (VPNS) IN MODERN IT: FUNDAMENTALS, ARCHITECTURE, AND USE CASES

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Introduction

A **Virtual Private Network (VPN)** is an internet security technology that allows users or networks to communicate over a public network as if they were directly connected to a private network. VPNs achieve this by using **encryption** to create secure, private tunnels through unsecured infrastructure. In practice, data passing through a VPN is encapsulated and encrypted, so even if intercepted on the open Internet it remains unreadable to unauthorized parties. VPNs have long been fundamental in IT for extending secure connectivity to remote users and linking distributed sites. With the rise of remote work and cloud computing, VPN usage has become ubiquitous: as of 2024, roughly 80% of organizations rely on VPNs to secure remote employee access, underscoring the shift toward hybrid work environments. This report provides a technical overview of VPN fundamentals – including VPN types, tunneling protocols, and encryption standards – and examines VPN architecture (clients, gateways, authentication, and key exchange). It also explores the role of VPNs in various IT contexts (remote work, secure communications, hybrid cloud, and access control) and analyzes their importance in cybersecurity strategies for protecting data against threats like man-in-the-middle attacks. Furthermore, we compare VPNs with emerging alternatives such as Zero Trust Network Access (ZTNA), as well as with other network technologies like MPLS and proxy servers. Finally, industry-specific VPN use cases are discussed across corporate IT, finance, healthcare, education, and government sectors.

VPN Concept and Tunneling: At its core, a VPN creates a *virtual* encrypted tunnel through which private traffic is sent across a public network (typically the Internet). This tunneling encapsulates the data packets, hiding their content and ensuring they safely reach the intended private network. Encryption scrambles the data so that only those with the correct cryptographic keys can decrypt and read it. As a result, VPN connections remain private even if they traverse shared infrastructure – for example, an employee’s database queries from home can securely transit the open Internet without leaking sensitive information to eavesdroppers. By combining *data encapsulation* with strong *encryption*, VPNs allow organizations to extend their secure internal networks to remote locations and users.

Types of VPNs: There are two primary categories of VPN in enterprise use, distinguished by what they connect:

- **Remote Access VPN:** A remote access (or *client-to-site*) VPN connects individual users to a private network. The user runs VPN client software which tunnels their device’s traffic to a VPN server (gateway) on the organization’s network. This allows remote employees to access intranet resources as if their device were physically on the local network. All communication

between the remote client and the VPN gateway is encrypted, protecting it from interception as it travels over the Internet. Remote access VPNs have become critical for telework, enabling secure communication for employees working from home, traveling, or on public Wi-Fi networks.

• **Site-to-Site VPN:** A site-to-site (or *gateway-to-gateway*) VPN links two networks (such as branch offices to headquarters) via dedicated VPN gateways at each site. The gateways establish an encrypted tunnel between the two LANs over the Internet, routing traffic between the sites securely. Individual users on those networks do not need VPN client software; the connection is handled transparently by the network routers or firewalls acting as VPN endpoints. This effectively merges the networks into a single private network over a wide area. Site-to-site VPNs are widely used to connect branch offices, datacenters, or cloud networks to on-premises networks.

• **Host-to-Host VPN:** In some cases, a VPN can connect just two individual hosts. This is a peer-to-peer VPN where one machine's VPN service connects directly to another's. Host-to-host VPNs are used to secure specific server-to-server communications or to allow a single authorized client to access a protected server over an encrypted link. This is less common than the above types, but useful for tightly controlling access to sensitive resources (the server only accepts connections through the VPN from a known client).

VPN Tunneling Protocols: VPNs can be implemented with various tunneling protocols, each with different mechanisms and security features. Key VPN protocols include:

• **PPTP (Point-to-Point Tunneling Protocol):** An older protocol (developed in the 1990s by Microsoft) that was one of the first widely supported VPN methods. PPTP encapsulates PPP (Point-to-Point Protocol) traffic over IP (using a TCP control channel and GRE tunnel) to send data between a client and server. While easy to set up and fast, PPTP is no longer considered secure – it relies on outdated encryption (Microsoft's MPPE using RC4 and MS-CHAPv2 authentication) which has known vulnerabilities. PPTP's weak encryption and multiple security flaws make it unsuitable for sensitive data. Modern enterprises avoid PPTP except in legacy scenarios where compatibility and speed matter more than security. In summary, **PPTP is largely obsolete due to its weak encryption and should not be used to protect confidential information**.

• **L2TP/IPsec (Layer 2 Tunneling Protocol with IPsec):** L2TP by itself is a tunneling protocol (an evolution of PPTP and L2F) that provides no encryption; it is typically paired with **IPsec (Internet Protocol Security)** to provide encryption and authentication to the tunneled traffic. In an L2TP/IPsec VPN, L2TP encapsulates the data (often PPP frames) and IPsec (using the ESP protocol) encrypts those packets and handles secure key exchange. This combo is widely supported on many devices and offers strong security (IPsec provides robust encryption like AES). L2TP/IPsec is often used for site-to-site VPNs and was a common choice for remote access before newer protocols emerged. Advantages include broad compatibility and relatively straightforward configuration, though performance can be lower due to the double encapsulation overhead. Firewalls or NAT can also pose challenges to L2TP/IPsec unless NAT-Traversal is enabled. Despite being older, L2TP/IPsec remains in use for its balance of security and compatibility, especially in corporate VPNs connecting branch offices.

• **OpenVPN:** OpenVPN is a popular open-source VPN protocol known for its flexibility and strong security. It uses SSL/TLS for key exchange and can encapsulate traffic over either UDP or TCP ports. OpenVPN establishes an encrypted tunnel by leveraging the same encryption primitives used in HTTPS – typically using the OpenSSL library with ciphers like AES-256 for encryption and TLS for authentication and key negotiation. Because it can run on any port (even TCP 443), OpenVPN is adept at traversing network obstacles and firewalls by masquerading as normal SSL traffic. It supports both point-to-point tunnels and site-to-site configurations in routed or bridged modes. OpenVPN's strengths include its **strong encryption (often AES-256) and peer-reviewed open-source code**, which has been audited by the security community. This makes it highly trusted for enterprise use. Many companies deploy OpenVPN for remote access VPN services due to its security and cross-platform client availability. The downside is that OpenVPN is not built into mainstream operating systems by default, and it can be complex to configure for newcomers. Overall, OpenVPN provides a robust, configurable VPN solution that remains a de facto standard for secure VPN services in many organizations.

• **WireGuard:** WireGuard is a modern VPN protocol (introduced in 2015) that has gained rapid popularity for its simplicity and performance. Unlike the older protocols, WireGuard was designed to be *lean and fast* while using state-of-the-art cryptography. Its codebase is only a few thousand lines (significantly smaller than OpenVPN or IPsec), which reduces complexity and potential vulnerabilities. WireGuard uses UDP for transport and employs a fixed set of contemporary ciphers (such as the ChaCha20 symmetric cipher for encryption, along with Poly1305 for authentication, and Curve25519 for key exchange). It forgoes negotiable algorithms in favor of opinionated choices considered secure by default. WireGuard's protocol establishes the tunnel using a technique called *cryptokey routing*: each client is assigned a static IP within the VPN and public keys are mapped to these IPs for routing. This makes setup very straightforward – essentially exchanging public keys between peers – and connections can be extremely quick to establish. In practice, WireGuard offers considerably higher throughput and lower latency compared to OpenVPN or IPsec, and its roaming capabilities (handling client IP changes seamlessly) are excellent. It is well-suited for mobile users or high-performance site-to-site links. WireGuard has been integrated into the Linux kernel and is available on all major platforms, making it easy to deploy. One consideration is that as a newer protocol, it doesn't have decades of battle-hardening; however, its strong design and scrutiny by cryptographers have led many experts to embrace it. **In summary, WireGuard provides fast and efficient VPN tunneling with cutting-edge encryption, and is increasingly favored as a VPN solution for modern needs**.

Encryption Standards in VPNs: VPN security relies heavily on strong encryption. Modern VPN implementations use robust encryption algorithms and key lengths to ensure data confidentiality. A common standard is **AES (Advanced Encryption Standard)** with 256-bit keys (AES-256), which is considered military-grade encryption; AES-256 is so secure that it's approved for top-secret government communications. OpenVPN and IPsec typically use AES-256 by default for encrypting the tunnel traffic. Newer protocols like WireGuard use the **ChaCha20** cipher (specifically an extended variant, XChaCha20) for encryption, paired with the Poly1305 message authentication code – this combination is also highly secure and performant. In contrast, older protocols have used weaker ciphers: PPTP's encryption (MPPE) was based on

the RC4 cipher with 128-bit keys and is considered cryptographically broken, which is a key reason PPTP is deprecated. L2TP/IPsec and IKEv2/IPsec can use a suite of strong algorithms (AES, or the older 3DES for compatibility, along with SHA-1/SHA-256 for hashing, etc.), all negotiable during tunnel setup. The **key exchange** processes (like TLS handshakes in OpenVPN or the IKE protocol in IPsec) often use asymmetric cryptography (RSA or ECDSA keys, Diffie-Hellman/Elliptic Curve Diffie-Hellman for generating shared secrets) to establish a secure session key. For example, IPsec's IKEv2 protocol performs a Diffie-Hellman exchange between the VPN peers to derive encryption keys and uses digital certificates or pre-shared keys for authentication. The result is an **encrypted VPN tunnel** in which all transmitted data is confidentiality-protected and integrity-checked. In summary, today's VPNs employ strong cryptographic standards (AES, ChaCha20, etc.) to meet high security requirements, and industry regulations often mandate such standards (e.g., payment card industry rules require VPN traffic to use at least 3DES or AES encryption).

Behind the scenes, a VPN consists of several architectural components working together to establish and maintain the secure tunnel. The typical VPN architecture includes **VPN clients**, **VPN servers/gateways**, and supporting elements for authentication and key management:

- **VPN Client (Endpoint Device):** This is the device or software application that initiates a VPN connection. For remote access VPNs, the client is usually a software program or built-in OS feature on the user's laptop, smartphone, or desktop. It is responsible for encapsulating the user's traffic into the VPN tunnel and encrypting it before sending. The client holds the user's credentials and typically some form of cryptographic material (e.g. a pre-shared key, digital certificate, or its own key pair for encryption). When a user connects, the VPN client negotiates with the VPN server/gateway to establish the tunnel (e.g., performing an SSL/TLS handshake for OpenVPN or an IKE exchange for IPsec). In site-to-site VPNs, the "client" functionality is handled by a router or firewall device – essentially the site's gateway acts as a VPN client (and server) to connect to the peer at the other site. In all cases, the client is an *endpoint* that encapsulates outbound traffic and decapsulates inbound traffic.

- **VPN Server / Gateway:** The VPN server (often called a **VPN gateway** when referring to network appliances) is the entity on the network's side that terminates the VPN connection. It could be a dedicated VPN appliance, a firewall/router with VPN capabilities, or a software service on a server. The gateway receives incoming VPN connection requests from clients, authenticates them, and if authorized, establishes the encrypted tunnel to the client. In remote access scenarios, the VPN server is the single point that all clients connect into to gain access to the internal network. In site-to-site scenarios, each site's gateway connects to the peer gateway. For example, in an enterprise connecting to a cloud network, the cloud provider might provide a **VPN gateway** (AWS calls it a Virtual Private Gateway) attached to the cloud VPC, while the on-premises side uses a **customer gateway device** – these two act as the VPN endpoints for the tunnel. The VPN gateway is responsible for routing VPN traffic to the appropriate internal networks once decrypted. It often also enforces access policies (controlling what resources a VPN user or site may reach).

- **Authentication Methods:** A critical part of VPN architecture is ensuring that only authorized parties can establish tunnels. **Authentication** occurs at two levels: the *device level* (authenticating the VPN peers) and the *user level* (authenticating the person/device using the

VPN, for remote access). For device-level authentication, IPsec VPNs may use *pre-shared keys (PSK)* – a secret known to both sides – or *digital certificates* (PKI) to verify each other's identity during the IKE handshake. SSL/TLS-based VPNs like OpenVPN likewise use certificates or a TLS pre-shared key for server authentication, and often client certificates for client auth. In enterprise remote access VPNs, it's common to integrate with directory services (LDAP/Active Directory or RADIUS servers) so that users authenticate with their organization credentials (username/password, tokens) in addition to the VPN protocol's own handshakes. Multi-factor authentication (MFA) is also widely implemented – for instance, a user may need a one-time OTP code or push confirmation on their phone in addition to their password when logging in to the VPN. The process typically goes: the user initiates a connection, the VPN gateway prompts for credentials (or validates the client certificate), and only upon successful authentication does it proceed to finalize the tunnel setup. In summary, robust authentication – often combining something the user knows (password), something they have (token/cert), or something they are (biometric) – is used to prevent unauthorized access to VPNs.

- **Key Exchange and Encryption Setup:** Once authentication is successful, the VPN peers must agree on encryption keys and parameters to use for the session. Protocols like **Internet Key Exchange (IKE)** (for IPsec) handle this automatically as part of their negotiation phase. In an IPsec VPN, IKE (v2 in modern setups) negotiates the cryptographic algorithms to use (encryption cipher, integrity hash, Diffie-Hellman group, etc.), performs a Diffie-Hellman key exchange to securely derive shared secret keys, and establishes a secure *IPsec Security Association (SA)* which contains the encryption keys and session parameters. This happens in a "phase 1" where a secure control channel is created, followed by a "phase 2" where actual data encryption keys (for the ESP tunnel) are established. In SSL/TLS-based VPNs, the TLS handshake serves a similar role: the client and server exchange random values and either use RSA/ECDHE or Diffie-Hellman to derive a session key, all while the server (and optionally client) is authenticated via certificates. The end result in both cases is that both VPN endpoints know a set of symmetric keys to encrypt and decrypt the data passing through the tunnel. These keys are usually rotated or re-negotiated periodically (for example, IPsec SAs have lifetimes after which rekeying happens) to maintain security. The *encryption component* of the VPN architecture is often implemented in software (OpenVPN's user-space process or WireGuard's kernel module) or hardware-accelerated (many firewalls have crypto ASICs to handle IPsec encryption/decryption). From the user's perspective, this key exchange is invisible – it occurs during the connection setup, often in just a second or two – after which the **VPN tunnel is established** and ready to carry encrypted traffic.
- **Networking and Addressing:** Another architectural aspect is how VPN clients are addressed and integrated into the network. In remote access VPNs, the VPN server typically assigns an IP address from an internal **VPN address pool** to the client. This IP is what the client will use for all traffic sent into the tunnel, effectively placing the client "inside" the network IP space. For example, a company's VPN might give remote clients an IP in a subnet like 10.0.10.x which is only used for VPN connections. The VPN gateway will route traffic from the client's VPN IP to internal resources and vice versa. In contrast, in site-to-site VPNs, each LAN keeps its own addressing, but the VPN gateways know which subnets are on the other side and route them via the tunnel.

Routing is configured so that any packets destined for the remote site's subnet are encrypted and sent through the VPN. Often, internal routing protocols or static routes handle this. Split-tunneling is another consideration: an organization can decide whether the VPN client should send *all* its traffic through the VPN (including Internet-bound traffic) or only traffic intended for the private network, while sending other traffic out locally. *Full-tunnel VPN* means everything is routed to the VPN (often for security, to enforce web filtering, etc.), whereas *split-tunnel* means only certain prefixes (e.g., company intranet subnets) go via VPN and the rest (like general Internet browsing) goes directly out the local network. This is configured on the VPN server and pushed to the client. Some security policies disallow split tunneling because it can introduce risk (an attacker on the local network could potentially reach the VPN tunnel if the client is simultaneously connected to an insecure network), while others prefer it to reduce bandwidth on the VPN concentrator and improve performance.

In summary, VPN architecture involves a client and server establishing a secure tunnel through mutual authentication and cryptographic key exchange. The **VPN client** encrypts data from the user and sends it to the **VPN gateway**, which decrypts it and forwards it into the private network (and vice versa for return traffic). Strong authentication (passwords, certificates, MFA) ensures only authorized users/devices create tunnels, and protocols like IKE or TLS manage the exchange of keys that underpin encryption. Through this architecture, VPNs extend the enterprise network across insecure environments while maintaining the confidentiality and integrity of communications.

VPN technology is applied in a variety of ways in today's IT environments. Key contexts include enabling remote work, securing communications over untrusted networks, connecting cloud resources with on-premises infrastructure, and serving as a mechanism for network access control. Below we explore these use cases:

One of the most prominent roles of VPNs is to facilitate **remote work** by providing secure communication channels for employees outside the office. In the era of widespread telecommuting and *work-from-anywhere* policies, VPNs have become a staple of IT infrastructure. By connecting through a VPN, remote users can safely access company email, file shares, intranet web applications, and other internal systems from home or while traveling. The VPN tunnel encrypts all traffic, so using a VPN on a public Wi-Fi (like a coffee shop or airport) protects against eavesdroppers and man-in-the-middle attacks – any intercepted data appears as gibberish to an attacker. This encryption assures that sensitive business communications (emails, VoIP calls, database queries, etc.) cannot be read or tampered with by outsiders on the path. In practical terms, a remote user's experience via VPN is as if they extended a virtual Ethernet cable from their device to the corporate network.

The COVID-19 pandemic massively accelerated this remote work trend, and VPN usage scaled up accordingly. By 2023-2024, studies showed that **over 80% of organizations** are using VPN services to secure their remote workforce's access to corporate resources. VPNs became a first line of defense for companies to ensure that employees working from home do so through an IT-approved secure connection. Along with endpoint security measures, the VPN forms a secure conduit, mitigating risks of data leakage over home or public networks. It also enables enforcement of company network policies on remote users (for instance, forcing all traffic through the company's firewall/content filters via the VPN).

Secure communication is not just for employees – VPNs are also used for **safe communication between sites or partners**. Companies often use site-to-site VPNs to communicate securely with business partners, contractors, or between subsidiary companies, especially when exchanging confidential data. Rather than sending data over the Internet in the clear, establishing a VPN between the two parties ensures an encrypted link. For example, two companies collaborating on a project might set up a site-to-site VPN so that their development servers can sync data securely, with each IT team controlling one end of the tunnel. Even smaller scale, some organizations provide client VPN access to external collaborators or vendors, granting them restricted access to internal systems through a secure path, instead of exposing those systems directly to the internet.

In summary, VPNs are indispensable for remote work and distributed teams. They **enable secure communications over any distance**, giving remote users and offices a trusted way to connect. By doing so, VPNs help maintain productivity and collaboration without sacrificing security, effectively extending the private, secure network environment wherever it is needed.

VPNs also play a crucial role in **hybrid cloud** and multi-cloud IT architectures. A hybrid cloud is when an organization integrates its on-premises IT infrastructure with cloud services (public cloud providers like AWS, Azure, Google Cloud). To securely link these environments, companies frequently use site-to-site VPN connections. For instance, an enterprise can extend its internal network into an Amazon Virtual Private Cloud (VPC) by configuring an IPsec VPN between its on-premises VPN gateway and the AWS VPN Gateway attached to the VPC. This creates an encrypted pipe through the internet such that cloud-based servers in the VPC can communicate with on-premises servers as if they were on the same network. Cloud providers provide managed VPN endpoints (AWS Virtual Private Gateway, Azure VPN Gateway, etc.) to facilitate this, and the customer configures their router or firewall on-prem to connect to it. The result is a seamless extension of the company's network to the cloud, protected by VPN encryption.

Use cases in this context include cloud backup and storage (securely transferring data to cloud storage over VPN), cloud bursting (securely connecting to cloud compute resources as extensions of the internal network), and hybrid applications where components spread between data center and cloud need a secure communication channel. Without VPNs (or similar secure links), organizations would have to expose services over the public internet with individual encryption, which is more complex and less secure overall. VPNs simplify it by **encapsulating all inter-environment traffic in one secure tunnel**.

Additionally, multi-cloud setups (using multiple cloud providers) can be interconnected with VPN mesh networks. For example, a company might have resources in Azure and AWS that need to talk privately; a VPN tunnel can be established directly between those cloud environments (or more commonly, each cloud environment VPNs back to the on-prem hub). Some modern architectures use software-defined networking (SD-WAN) to connect sites and clouds, essentially orchestrating many VPN tunnels in an automated way for resilience and performance. Under the hood, however, they are still leveraging VPN encryption (often IPsec) to secure the traffic between all the endpoints.

In summary, VPNs enable **secure hybrid cloud infrastructure** by linking disparate networks (on-premises sites and cloud networks) into a unified secure network.

They are a fundamental tool for enterprises to adopt cloud computing while maintaining secure, private connectivity and control over their data flows.

Another role VPNs serve is acting as a gatekeeper for accessing restricted networks or resources – essentially a tool for **access control**. Many organizations choose not to expose sensitive internal applications directly to the internet. Instead, they make those resources available *only* to users who are "inside" the network. VPNs provide a way for authorized external users to get **inside the network perimeter** virtually, after which they can reach those protected services. In this model, the VPN is a first layer of access control: if you aren't connected through the VPN (and authenticated), you cannot even see or talk to certain systems. For example, an internal HR database or finance system might be blocked from any internet access; employees at home must first connect via VPN, and only then can they use those applications as if on the local network. This keeps the resources hidden from direct attack on the open internet.

VPN-based access control is commonly used for administrative interfaces, databases, or development servers – basically anything sensitive that you want to shield from exposure. It aligns with the classic "castle-and-moat" security model: the VPN is the drawbridge over the moat, allowing trusted users in while keeping everyone else out. Once on the VPN, users often have broad access to the network (which is one of the drawbacks discussed later in comparison to zero trust approaches). That said, policies can also be applied to limit what a VPN user can reach. Many VPN systems integrate with directory groups, so that, for instance, members of the database admin team who VPN in are allowed to access database servers, but no other VPN users can reach those servers. This is achieved by firewall rules on the VPN gateway or internal network that filter traffic based on the user's VPN identity or source IP range (some VPNs assign different IP pools to different user groups to facilitate this). Thus, VPNs can be coupled with fine-grained access control rules to implement a form of **network segmentation** – even remote users only get access to the specific segment of the network they need.

Enforcing access control via VPN became a double-edged sword. On one hand, it's effective in that it **keeps sensitive resources off the public Internet** entirely (you can't attack what you can't reach). On the other hand, once a user is on the VPN, if not carefully restricted, they might move laterally across the network. Traditionally, VPNs were often an all-or-nothing trust: if you have the VPN, you're treated as an insider. This is changing with more modern approaches, but in many organizations it still holds that the VPN is a prerequisite for accessing critical systems.

Overall, VPNs have been a core component in enterprise **identity and access management** strategies. By requiring VPN connectivity (with proper authentication) for access, companies add an extra security layer. It's not just "do you have the right password for the application" but also "are you connecting from a trusted, encrypted network path as an authenticated member of our organization." This significantly reduces exposure. Cloudflare's security learning center notes that VPNs are commonly used for access control and can keep certain resources hidden from outsiders. However, it also hints that there are alternatives arising because VPNs in this role have limitations (single point of entry, broad network access, etc.). We will discuss those alternatives (like ZTNA) shortly. Nevertheless, in current IT environments, using VPNs to enforce network access policies is standard practice – for example, many

universities require VPN for accessing library resources from off-campus, and many enterprises require VPN for any access to internal apps when not in the office. This ensures that even on untrusted networks, access is funneled through an encrypted, authenticated channel, thereby upholding the organization's security posture.

VPNs are a vital element of cybersecurity strategy for protecting data in transit and defending against certain network-based threats. Key security benefits provided by VPN implementations include:

- **Encryption Against Eavesdropping and Man-in-the-Middle (MitM) Attacks:** Because VPNs encrypt all traffic between the client and server, they dramatically reduce the risk of interception. If an attacker on the same network (for example, a hacker snooping on public Wi-Fi, or malware-infected router in a coffee shop) tries to eavesdrop on a VPN user's communications, the attacker would only see ciphertext (encrypted data) that is computationally infeasible to decipher. This effectively thwarts most **man-in-the-middle attacks** on the network link – the VPN user's web browsing, emails, and data transfers cannot be read or manipulated by the interceptor. The same applies within an enterprise: if an employee is connected via VPN from a potentially hostile environment, the encryption ensures that even if someone intercepts the traffic between the employee and the company network, it's not readable. Additionally, the integrity checks in VPN protocols mean that any attempt to alter the data (for instance, to inject malicious packets) would be detected and dropped. Thus, VPNs provide **confidentiality and integrity**, two core tenets of cybersecurity, for data in transit. This is especially important when dealing with sensitive information like customer data, credentials, financial transactions, or intellectual property being transmitted over networks that could be monitored.
- **Protection on Untrusted Networks:** VPNs allow users to convert an untrusted network into an effectively trusted extension of their private network. When a user connects from a hotel, airport, or café network, there is an inherent risk because such networks can be poorly secured or even intentionally malicious (rogue Wi-Fi hotspots). Using a VPN on such networks immediately wraps the connection in encryption, so even if the local network is compromised, the user's session is safe. It's as if the user's machine has a secure "tunnel" that other devices on the local LAN cannot peer into. This not only protects against snooping but also can prevent certain network-based attacks. For example, without a VPN, an attacker could potentially perform ARP spoofing or DNS poisoning on the local network to redirect the user's traffic. With a VPN, the user's traffic is directed straight to the VPN server, ignoring local network name resolvers (in many setups) and being encrypted, which can neutralize those local attack vectors. In short, **VPNs mitigate the risks of using untrusted networks** by enforcing encrypted communications and often by applying consistent DNS and routing policies through the tunnel (reducing reliance on any potentially compromised local network services).
- **Preventing Data Leaks and Ensuring Privacy:** By design, VPNs encapsulate private data and send it through a single secure channel. This means that sensitive data is not broadcast in the clear or sent via protocols that could leak information. A corporate VPN will often force all internal application traffic through the secure tunnel, so things like internal file server transfers, intranet site use, or proprietary protocol communications never hit the public internet directly. This containment significantly reduces the chance of *data leaks*. For example, an employee checking email through a VPN is effectively pulling those emails through an

encrypted stream, whereas without a VPN they might accidentally use an insecure protocol or connect to a fake access point and leak credentials. VPN logs on the server can also provide an audit trail of connections, which helps in monitoring and detecting anomalies (e.g., if a user's account is used at an odd time, security can be alerted). Many compliance regimes (like HIPAA for health data or PCI DSS for payment data) either require or strongly recommend encryption for data in transit. VPNs provide an out-of-the-box way to encrypt all data between specific endpoints, helping organizations meet these requirements. In healthcare, for instance, using a VPN for remote access ensures that any electronic patient health information transmitted is encrypted and protected as required by regulations.

- **Guarding Against Untrusted Endpoint Risks:** While VPNs primarily protect data in transit, they also play an indirect role in endpoint security strategy. By funneling traffic through a company-controlled gateway, security teams can impose controls such as intrusion detection systems, web filtering, or malware scanning on that traffic. For example, when a remote worker uses a full-tunnel VPN, all their web browsing can be run through the corporate secure web gateway or firewall which might block malicious sites – protection they would not have if directly browsing on a public network. Additionally, some advanced VPN solutions verify the security posture of the connecting device (a practice sometimes called *Network Access Control (NAC)* or health checks) before allowing the connection – checking if the device has up-to-date antivirus, patches, etc. This can prevent compromised or non-compliant devices from gaining VPN access and potentially injecting threats into the network. In this way, VPNs can be part of a **defense-in-depth** approach, ensuring that remote connections are not a weak link.
- **Limiting Attack Surface:** VPNs, when used for access control, reduce the attack surface by closing off services from the open internet. Attackers scanning the internet for vulnerabilities will not see a company's database or internal web app – those services are invisible, tucked behind the VPN gateway. The VPN gateway itself becomes the focus: it's a single point that must be fortified (with patches, updates, strong authentication, etc.), but it's easier to protect one door than an entire neighborhood of doors. That said, VPN concentrators themselves have been targets for attackers, and vulnerabilities in VPN servers (e.g., in widely used corporate VPN appliances) have led to breaches when not promptly patched. Even so, from a strategic view, using a VPN is a sound security practice because it **eliminates the need to expose many individual services**; only the VPN needs to be exposed. It's also worth noting that the majority of organizations still see VPNs as essential: they continue to trust VPNs for secure connectivity, even as new paradigms like zero trust are discussed.

In conclusion, VPNs are a cornerstone of network cybersecurity. They provide encrypted tunnels that preserve confidentiality and integrity of data, they allow safe use of untrusted networks, and they integrate with access controls to keep private systems private. However, it's important to acknowledge that VPNs are not a silver bullet – they must be properly configured and maintained. Poorly secured VPN credentials or unpatched VPN server software can be an avenue for attackers. Hence, many organizations combine VPN usage with other security measures (strong authentication, strict user permissions, network monitoring) for a holistic approach. Nonetheless, as a technology, VPNs address a fundamental security need: **protecting data in transit and extending the secure perimeter to wherever it needs to go**.

As the cybersecurity landscape evolves, organizations are considering alternatives or supplements to traditional VPNs for secure connectivity. Here we compare VPNs with a few notable technologies: Zero Trust Network Access (ZTNA), MPLS, and proxy servers.

VPN vs. Zero Trust Network Access (ZTNA)

Zero Trust Network Access (ZTNA) is a modern approach that differs fundamentally from VPNs. Traditional VPNs implicitly trust a user once they are connected – the user gains broad network access (often to an entire subnet). In contrast, ZTNA follows the principle of "never trust, always verify." Under zero trust, no user or device is inherently trusted just because it's "inside" the network; instead, access to specific applications or data is granted on a case-by-case basis and requires continuous verification of the user's identity, device posture, and other context. ZTNA typically does not provide layer-3 network access at all – instead of placing the user on an inside network, the ZTNA broker (usually a cloud service or on-prem gateway) proxies user connections *only* to the applications the user is authorized for, and nothing else.

From a **security** standpoint, ZTNA offers more granular control than VPN. Users are given the least privilege needed – for example, an employee might be allowed to use a particular finance application and nothing more, whereas the same employee on a VPN might technically have access to the entire finance subnet even if they only need one app. This *minimizes the attack surface* and risk of lateral movement if an account is compromised. VPNs, on the other hand, excel at providing an encrypted tunnel, but once that tunnel is open, the user can often reach many systems (unless additional internal firewalls are in place).

In terms of **management and scalability**, VPNs can become complex as organizations grow. Managing hundreds or thousands of VPN users means handling client software on devices, scaling VPN servers or concentrators for throughput, and dealing with potential performance issues as all traffic might be hair-pinned through corporate data centers. ZTNA solutions are often cloud-delivered and can scale more easily by design – they authenticate users and then connect them to nearest service points for the specific apps, generally resulting in less backhaul and potentially better performance. ZTNA can also simplify management by centralizing policy definitions (who can access what application) without worrying about network segments and IP addresses.

Performance and user experience can also differ. VPNs backhaul traffic – for instance, a user in one city connecting to a VPN at headquarters in another city might then go out to a cloud app back in the user's city, creating unnecessary latency. ZTNA often allows direct connectivity through a distributed cloud or nearest gateway to the app, optimizing the path.

Additionally, ZTNA is typically "clientless" or uses lightweight agents that dynamically connect when needed, often making it seamless to the user (they click an app and behind the scenes an authenticated channel is created). VPNs usually require the user to actively launch a client and connect to the VPN before doing their work, which is an extra step.

In summary, **ZTNA provides a more fine-grained, identity-centric model for remote access**, focusing on applications rather than networks. It enforces continuous authentication and significantly limits what an external user can do, aligning with zero trust philosophy. Traditional **VPNs provide secure tunnels and are simpler to deploy for full network access**, but they grant a broad level of trust to users once connected and can face scalability challenges. A concise comparison from a recent analysis: *"ZTNA offers a more modern and robust security framework*

with granular access controls, making it highly secure and scalable. VPNs, on the other hand, provide a simple solution for secure remote access and privacy protection, but face challenges with scalability and performance.". Many organizations are not eliminating VPNs overnight but are moving towards incorporating ZTNA for certain use cases, especially as remote work persists. For now, VPNs and ZTNA often coexist – VPNs for broad network access needs and legacy applications, ZTNA for more controlled access to critical apps – but the trend suggests a gradual shift toward zero-trust models in the long term.

VPN vs. MPLS

MPLS (Multi-Protocol Label Switching) is not a remote access technology but rather a private networking technique often compared with VPNs for connecting multiple sites. An MPLS network is a service typically provided by telecom carriers where the customer's sites are interconnected through the provider's private network, with traffic separation achieved by label-switching rather than encryption. In effect, an MPLS WAN is a private network (OSI layer 2/3) linking locations, offering reliable and low-latency connectivity with Quality of Service (QoS) support for prioritizing traffic. Companies historically used MPLS circuits (like leased lines, T1/E1, etc.) to connect offices before VPN over Internet became popular.

Key differences: A major difference is **encryption**. VPNs encrypt data over the public internet, whereas basic MPLS does not encrypt data by default (it's assumed to be a closed network provided by the carrier). Because MPLS traffic isn't traveling over the open internet and is segregated by the MPLS mechanism, it is relatively secure from outside threats; however, if an attacker were able to tap into the carrier's network, MPLS traffic could be read unless an additional encryption layer is used. In practice, some organizations even run VPN on top of MPLS links for double security, but many rely on the carrier's network segregation. In terms of security, MPLS is often perceived as **secure but not as inherently confidential as VPN** – it's "secure" in that outsiders normally can't access it, and it's not subject to internet-based attacks, but it doesn't meet the "encrypted" requirement unless combined with encryption. VPNs, by contrast, operate over the shared internet but use strong encryption to ensure confidentiality.

Performance and reliability: MPLS networks typically provide **better performance and reliability** than site-to-site VPNs over the internet. MPLS paths are optimized by the provider to be efficient and can guarantee bandwidth and low latency via QoS, making them ideal for real-time applications (voice, video) between offices. There is also no encryption overhead in MPLS itself, so latency is very low. VPNs over the internet can suffer from the unpredictability of internet routing, variable latency, and generally lower reliability. However, improvements in broadband speeds and stability, and technologies like SD-WAN (which can dynamically choose optimal paths), have narrowed this gap. Additionally, VPN performance has improved with newer protocols and hardware acceleration. But if absolute reliability and consistent latency are required (for example, a financial trading firm linking data centers), MPLS has traditionally been the gold standard.

Cost and flexibility: MPLS services tend to be significantly more **expensive** than using internet-based VPNs. They often involve long-term contracts with carriers and costs that scale with bandwidth. VPNs, using the public internet, are much cheaper – essentially the cost of an internet connection at each site and the VPN equipment. VPNs are thus very attractive to organizations looking to reduce WAN costs, even if performance might be a bit lower.

In terms of **flexibility**, VPNs are generally easier to set up and reconfigure. Adding a new site to a VPN mesh is under the company's control using internet links, whereas adding a site to an MPLS network requires coordination with the provider and possibly significant lead time and expense. VPNs can also work over any internet connection, giving more agility (e.g., you can quickly set up a temporary VPN over a 4G/5G wireless link for a remote office). MPLS is more static.

Use cases: Many companies now use a hybrid approach – critical sites might use MPLS for guaranteed performance, while also having VPN over internet as backup or for less-critical traffic. Others have replaced MPLS entirely with VPN-based SD-WAN solutions to save cost. Both VPNs and MPLS can coexist; in fact, **both can be used to create private networks connecting multiple sites**, but MPLS does it by creating a virtually dedicated network path, and VPN does it by **encrypting** over the public network. Some content from industry comparisons notes: *VPN offers encryption by default and is cheaper, whereas MPLS offers more consistent performance and reliability (with no encryption overhead) but at higher cost*. Importantly, if security is measured by encryption strength, VPN has the edge (since MPLS doesn't encrypt unless you add something on top). If security is measured by isolation from the public internet, MPLS has an edge (since there's no exposure to internet threats).

In summary, **VPN vs MPLS** is often a trade-off between cost/flexibility and performance/reliability. VPNs have democratized secure networking by using the inexpensive internet as a backbone with encryption to keep data safe. MPLS remains in use for enterprises that require stable, high-performance links and are willing to pay for it, but its dominance has waned as VPN technology and internet quality have improved. Most modern networks are trending towards internet-based VPN connectivity (often with SD-WAN intelligence) given the cost savings and sufficient performance for typical needs.

VPN vs. Proxy Servers

Both VPNs and proxies can be used to route traffic through an intermediary, but they operate at different layers and offer different levels of security. A **proxy server** (in the context of forward proxies) is an intermediary that handles requests from a client to another server, often used for web traffic (HTTP/HTTPS). When using a proxy, a specific application (like your web browser) is configured to send its traffic to the proxy; the proxy then forwards the request to the destination on behalf of the client, hence hiding the client's IP address from the destination. A **VPN**, on the other hand, routes *all* network traffic from a device (or network) through a VPN server by creating an IP-level tunnel.

Encryption: The most significant difference is that a VPN **encrypts all traffic** between the client and the VPN server, whereas a basic proxy typically does not add encryption (it may simply relay the traffic). For example, if you use an HTTP proxy and visit an http:// site, that traffic is in plaintext from the proxy to the site and possibly from you to the proxy as well. In contrast, a VPN would encrypt that HTTP traffic from your device all the way to the VPN server. (If the proxy is an HTTPS proxy or you're using an SSH tunnel as a proxy, there can be encryption in the channel to the proxy, but this is not common for standard proxy setups). **VPNs thus provide greater privacy and security** than most proxies, since they ensure the entire connection is encrypted and safe from eavesdropping.

Scope of traffic: VPNs work at the network layer, capturing all IP traffic from a device (or even a whole site in site-to-site scenarios). This means *all applications* – web browsers, email clients, messaging apps, etc. – get their traffic secured and tunneled. A proxy usually works at the application layer (e.g., a web proxy for HTTP). It will only handle traffic from apps configured to use it, and often only specific protocols. For instance, a HTTP proxy won't handle your FTP or Skype traffic. There are SOCKS proxies that are lower-level and can handle any kind of traffic, but the applications still need to be configured to use them. With a VPN, the operating system's networking is typically tunneled, requiring no special configuration per application (aside from installing the VPN). So from a **comprehensiveness** perspective, a VPN is a broader solution.

Anonymity and IP masking: Both proxies and VPNs can hide the user's real IP address from the destination server by substituting the proxy/VPN server's IP. However, proxies might add identifying headers (e.g., some proxies include the original IP in an X-Forwarded-For header in HTTP, unless configured not to), whereas VPNs do not – to the destination, traffic truly appears from the VPN server as if it's the client. Many people use commercial VPN services or proxies to achieve anonymity online or bypass geo-restrictions. In practice, a VPN is generally considered more private because of the encryption and because it covers all traffic (e.g., DNS queries from your device will also go through the VPN, whereas if you just set a browser proxy, your DNS might still go out locally, revealing your origin).

Use cases: Proxies are often used in corporate networks for caching and content filtering for web traffic, or to allow multiple users to share a single public IP. They are also used to bypass content restrictions (for example, using an open proxy to access blocked websites). VPNs are used for secure access and privacy more broadly. For instance, if one just wants to stream content available in another country, either a VPN or a proxy could work – but a VPN will encrypt and carry all traffic (which is more secure but might be overkill for that use), while a smart DNS or HTTP proxy might just handle the specific traffic needed for that service.

Performance: A proxy might have less overhead than a VPN because it may not be encrypting/decrypting (unless it's an HTTPS proxy which still usually just passes through the TLS). VPN encryption/decryption can add some CPU load and slight latency. However, the difference nowadays with efficient encryption is minor for most broadband connections. Still, someone might choose a proxy if they only care about IP address change and want to minimize any overhead.

In summary, the **key difference is encryption and scope**. A **VPN creates a secure encrypted tunnel for all traffic from a device or network**, making it a comprehensive security solution for remote access and privacy. A **proxy acts as an intermediary for specific application traffic and typically does not inherently provide encryption**, so it's more of a convenience or performance tool rather than a security tool. As one security comparison succinctly puts it: *"A VPN provides greater privacy and security than a proxy because it routes your traffic through a secure VPN server and encrypts your traffic. A proxy may hide your IP but won't necessarily encrypt the data, leaving it vulnerable."*.

It's worth noting that modern enterprise solutions often combine concepts: for example, ZTNA brokers function somewhat like proxies (brokering access to specific apps) but within an encrypted, authenticated framework – kind of marrying the proxy approach with VPN-grade

security. Traditional proxies and VPNs each have their place, but for securing an entire connection, VPNs are the more robust choice in an enterprise security strategy.

VPN technology is utilized across numerous industries to meet security, privacy, and connectivity requirements. Below are some industry-specific use cases and considerations:

- **Corporate Enterprise IT:** Businesses of all sizes use VPNs to connect remote employees and satellite offices to the central corporate network. Enterprises often deploy **remote access VPNs for teleworkers** (especially important for consulting firms, tech companies with flexible work, etc.) and **site-to-site VPNs to integrate branch offices**. VPNs enable secure file sharing, access to internal applications, and VoIP communications across locations. They form part of business continuity plans – employees can work from anywhere without exposing data. Large enterprises may use high-capacity VPN concentrators to handle thousands of simultaneous connections. Security policies enforce VPN usage on untrusted networks to prevent corporate data interception. Surveys indicate that virtually all large organizations use VPNs in some capacity; for instance, one report notes **96% of organizations still leverage VPNs** for remote connectivity. Thus, VPNs remain a backbone of corporate IT networking and security.
- **Financial Services:** Banks, investment firms, and payment processors handle highly sensitive financial data, so they heavily rely on VPNs to secure communications. Common uses include **VPN tunnels between branch banks and data center** (often using IPsec over dedicated lines or internet), and **remote access VPN for financial employees** who must securely connect from home or while traveling (ensuring client data and transactions are encrypted in transit). Many ATM networks even use VPNs over the internet to connect back to core banking systems securely. Regulatory standards like the PCI DSS (for credit card data) mandate strong encryption for any sensitive data over open networks; accordingly, financial institutions use VPNs with strong ciphers (often AES-256) to meet these requirements. Trading firms use VPNs to link to exchanges or brokers securely, as even milliseconds matter and they can't afford retransmissions due to poor security. In finance, **compliance is key** – VPN solutions must be FIPS 140-2 validated (using approved cryptographic modules) to satisfy auditors. Additionally, granular access control is implemented: for example, a financial advisor might VPN into a brokerage's network and only be allowed to access certain client databases. The VPN audit logs help in compliance reporting by documenting who accessed what and when. Overall, VPNs provide the confidentiality and integrity needed for financial data and transactions, forming an encrypted shield around the sector's critical networks.
- **Healthcare:** Hospitals, clinics, and healthcare providers use VPNs to protect patient data and comply with privacy laws like HIPAA. A prime use case is enabling healthcare professionals to securely access electronic health record (EHR) systems from outside the hospital – doctors on call can review patient charts from home via a VPN, or a billing specialist can work remotely with access to the hospital's billing system. **HIPAA regulations explicitly require encryption of electronic protected health information (ePHI) during transmission over networks**, and VPNs are a common way to achieve this for healthcare organizations. Many healthcare networks connect multiple sites (e.g., clinics to main hospital) over VPN tunnels, ensuring that patient records, medical imaging, and other data transfers are encrypted between facilities. Telemedicine applications use VPNs to secure video consultations and remote monitoring data. Furthermore, medical IoT devices or remote diagnostic tools might use VPN connections to send data back to

providers safely. In public health or research, VPNs allow researchers to access sensitive databases from universities securely. Healthcare organizations also often rely on third-party service providers (for radiology reads, insurance claims processing, etc.), and they extend VPN access to those partners so that data exchanges occur over encrypted channels rather than email or open internet. In essence, VPNs in healthcare create a **secure conduit for life-critical and privacy-critical information**, helping to uphold patient confidentiality and data security as mandated by law.

- **Education:** Universities and educational institutions utilize VPNs to allow students and faculty to securely access campus resources from off-campus. For example, many universities have a VPN service that students must use to reach library databases (due to licensing restrictions, many academic journals only allow campus IP ranges; a VPN extends the campus network to remote students). Faculty and IT staff use VPNs to administer campus servers from home or conference travel securely. Given the rise of remote learning and global collaboration, VPNs also enable safe access to virtual classrooms, research networks, or high-performance computing clusters for authorized users no matter where they are. Schools often have sensitive data (student records, research data) that need protection, so when that data is accessed remotely, VPN encryption provides peace of mind. In some cases, educational institutions in countries with internet censorship use VPNs to provide open internet access for academic research. Students themselves also learn about and use VPNs as part of cybersecurity and networking courses, often practicing with the university's own VPN systems. In summary, VPNs in education support **academic access and collaboration** by bridging the campus-network divide securely and by protecting intellectual property and personal data as it traverses external networks.
- **Government and Public Sector:** Government agencies heavily depend on VPNs for secure inter-agency and remote communications. Classified or sensitive government data must travel in encrypted form if sent over unclassified networks; government VPNs (often required to use approved encryption algorithms and hardware per national standards) facilitate this. Use cases range from law enforcement officers accessing criminal databases securely from their patrol vehicles (commonly done via VPN over cellular networks) to diplomats connecting back to their home country's secure network while abroad. Military and defense organizations use VPN-like tunneling (often with added layers of authentication and monitoring) to connect bases and forward units to central command securely. Many countries have a governmental secure network (e.g., NIPRNet/SIPRNet in the U.S. for unclassified/classified but sensitive traffic) that relies on encrypted tunnels across the broader internet or dedicated lines – essentially large-scale VPNs. Local governments (city halls, etc.) use VPNs to allow city employees to work remotely or to connect different offices (police, fire, public works) securely. Given the high stakes of government data, these VPNs are rigorously managed: for instance, the U.S. government mandates FIPS-validated encryption and often two-factor authentication for VPN access by federal employees. VPN technology also helps government agencies cooperate: when agencies or international allies need to share data, they might set up a site-to-site VPN between their networks with strict controls. **In essence, VPNs provide governments with a means to conduct their operations securely in cyberspace**, whether that's a teleworking civil servant or a covert agent transmitting data back to headquarters. They help protect national security information and ensure continuity of government functions securely.

Across all these sectors, a common thread is that VPNs help maintain **secure connectivity and compliance**. They are tailored slightly to each industry's needs (e.g., healthcare focusing on HIPAA compliance, finance on PCI DSS and encryption standards, government on classified data handling), but the fundamental benefit is the same: a VPN creates a trusted, encrypted link over untrusted networks, enabling business and services to proceed without exposing sensitive information.

Conclusion

VPNs have proven to be a foundational technology in information technology, enabling secure network connectivity across the boundaries of location and infrastructure. Technically, a VPN provides the mechanisms to authenticate users/devices and to encapsulate and encrypt data packets, creating a **private communication channel over public networks**. We explored how VPNs operate – from the fundamental types (remote access client-to-site VPNs and site-to-site tunnels) to the specific tunneling protocols like PPTP, L2TP/IPsec, OpenVPN, and WireGuard that each bring different balances of security, performance, and ease of deployment. VPN architecture involves clients and gateways performing cryptographic handshakes (IKE, SSL/TLS) and exchanging keys to forge an encrypted tunnel. Through strong encryption (AES, ChaCha20) and rigorous authentication methods, VPNs ensure that data in transit remains confidential and unaltered, even across untrusted networks.

The role of VPNs in modern IT cannot be overstated. They have been instrumental in **facilitating remote work**, especially in recent years, by allowing employees secure access to corporate networks from anywhere. VPNs form the backbone of secure communications – protecting against eavesdropping, man-in-the-middle attacks, and data leaks on Wi-Fi and other insecure networks. In hybrid cloud architectures, VPNs bridge on-premises and cloud resources, creating a unified secure environment for applications and data. As an access control tool, VPNs have traditionally guarded the gates of internal networks, admitting only authenticated users and thereby keeping critical resources hidden from the internet.

We also compared VPNs with emerging or alternative technologies. **Zero Trust Network Access (ZTNA)** represents a paradigm shift, advocating per-application access instead of network-wide access, and offers enhancements in granular security and scalability – though VPNs remain a simpler, well-understood solution for many use cases. We contrasted VPNs with **MPLS** networks, highlighting that while MPLS provides reliable private connectivity, it lacks inherent encryption, and VPNs have become a cost-effective way to securely connect sites over the internet. Additionally, we distinguished VPNs from **proxy servers**, noting that VPNs encrypt all traffic and operate at the network layer, whereas proxies typically don't encrypt and work at the application layer – making VPNs the more robust choice for comprehensive security.

Industry use cases demonstrate the versatility and necessity of VPNs: enterprises securing corporate data and supporting remote employees; banks and hospitals complying with encryption mandates and protecting client information; educational institutions extending learning resources securely; and governments safeguarding communications and national security data via encrypted channels. In each case, VPNs adapt to the requirements of confidentiality, integrity, and availability that the sector demands.

In closing, VPN technology continues to evolve. Protocol innovations like WireGuard show that VPNs can become faster and even more secure with a modern codebase.

At the same time, the rise of zero trust philosophies is influencing how organizations design remote access – often supplementing or layering on top of VPNs to tighten security further. There are also increasing considerations around VPN security management: ensuring VPN servers are patched (since they are a high-value target), using strong authentication to prevent breaches via stolen credentials, and monitoring VPN traffic for anomalies. VPNs are not a panacea, but they **remain a critical component of cybersecurity strategy**, creating an essential secure link in our interconnected world.

As companies and institutions continue to rely on distributed workforces and cloud services, VPNs provide a proven, reliable way to maintain secure communications. Whether used alone or in tandem with newer approaches, VPNs will likely persist as a fundamental building block of IT networks, embodying the principle that even over an untrusted internet, we can establish trust and privacy through technology.

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