

Final Reflection

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The internet is often perceived as a monolithic entity, a utility that just works. However, throughout the course of this term, I have come to understand the internet as a complex, hierarchical layering of protocols and physical infrastructure. The hourglass model of computer networks provides a potent abstraction, but it was only through the practical application of these concepts through my project work that fully illuminated my understanding. By dissecting computer networks from physical wires to user facing applications, I have found that computer networks don't just support our interactions with the world; they fundamentally shape the speed, reliability, and very nature of those interactions.

At the base of the hourglass lies the Subnetwork Layer, where bits are transformed into reality. While we often think of the modern web as wireless, my work on the Network Topology and Routing projects revealed the scale at which our online interactions are governed by physical infrastructure.

In my Network Topology project, I traced packets sent from Carleton College to destinations all around the globe. The latency data I collected provided clear evidence of the physical restraints governing the internet. For instance, my trace to the University of Cape Town took approximately 160ms just to traverse a submarine cable from Jacksonville to South Africa. This is not a software delay, but the time it takes light to travel through thousands of miles of submarine fiber optic cables. In my Routing project writeup, "The Internet's Hidden Highways," I noted that these physical jumps across the oceans are the bottlenecks where data can spend the vast majority of its time.

This layer dictates the baseline speed of the internet. No matter how optimized applications are, they are bound to the physics of the Subnetwork Layer. Even the fastest code must wait for the physical transport of photons through glass, as I observed in the transoceanic hops to Cape Town and Zurich. The internet, therefore, is not a cloud but a machine; for it to function, individual nodes must maintain a physical capacity to exchange data across the constraints of the real world.

Moving onto the Network Layer, we encounter the Internet Protocol (IP) and the concept of a network of networks. Interestingly, my findings demonstrated that this layer is less about any technology and more about business relationships and redundancy.

In my Routing project, I compared the traceroute data from my Network Topology project with BGP (Border Gateway Protocol) data from a Route Views collector in Chicago. This revealed a complex and redundant web of choices. While traceroute shows the preferred single path to a destination like Gonzaga University, BGP revealed that there were actually 17 available routes advertised. The implementation of BGP provides resilience to a network. If one path fails, we simply switch to another, preserving our interactions with the world even when physical infrastructure fails.

Furthermore, this layer reveals the hidden commercial and political interests that govern how we interact with the internet. My investigation into the firewalls I encountered when probing the University of Chile and University of Cape Town showed that network operators actively control the visibility of the internet. While they blocked my traceroute ICMP packets, making their networks appear dead to the outside world, BGP proved that they are advertising routes to their networks and are fully connected. This finding highlights that the access of the internet is a policy decision implemented at the Network Layer. Administrators can render their institutions invisible to certain tools while maintaining their presence to global conversations.

Finally, the pure dominance of commercial interests is starkly visible in the rise of hyperscalers. My BGP analysis of the path from Carleton to Gonzaga revealed a single hop from the Chicago Route View collector to Microsoft's network (AS8075). This path of one demonstrates how massive corporations have effectively flattened the network topology. They don't rely on the standard hierarchy of ISPs; They build their own private backbones, effectively becoming ISPs themselves. This produces an array of effects. For starters, hyperscalers can provide unmatched latency with networks that carry exclusively their own traffic. However, this hinders the potential power of the global internet. These hyperscalers are not transit networks, meaning they don't contribute to the speed of the rest of the internet. Together these effects have produced a problem of monoculture. These corporations have consolidated the power of the internet into just a few hands, meaning that if one of their networks fails it has catastrophic consequences for the internet as a whole.

Now that individual nodes can talk to each other and different networks can identify and connect to one another, we need a way to exchange information between hosts. The Transport Layer provides this functionality through TCP, prioritizing reliability, and UDP, prioritizing speed. My work on the Reliable Transport and DNS projects highlighted the inherent tradeoff in this layer between speed and reliability.

In my DNS project, I recognized that DNS queries are served over UDP. This choice provides low latency with a dropped packet simply being re-queried rather than waiting for the overhead of a 3 part handshake to reestablish connection. This choice

makes the lookup phase of our interactions nearly instantaneous, fundamentally altering our perception of the network. Because the gap between typing a URL and seeing a web page is so imperceptible, it creates the illusion that the internet is not a complex system of distant nodes, but an immediate, always available extension of our own computer's memory. The Transport Layer lets the Application Layer create an interface where retrieving a website from a server from Virginia feels like opening a file stored on one's own desktop.

Conversely, my Reliable Transport tutorial, "The Life, Death, and Miraculous Recovery of a TCP Connection," showcased the immense complexity required to guarantee stability and reliability throughout a connection. Through annotating a Wireshark trace, I witnessed the Seq/Ack dance that establishes the rules of engagement for any TCP connection. More importantly, I witnessed a catastrophic loss of connection when I halted my Wi-Fi connection and the flood of reliability mechanisms—Spurious Retransmissions, Duplicate ACKs, SACKs, and more—firing together to repair the stream without the user (me) needing to do a thing. This layer masks the inherent unreliability of its supporting layers, creating the illusion of seamless connections across the internet.

Finally, the Application Layer is where user meets network, where most people spend the entirety of their time interacting with the internet, and where we began this class. My experience implementing the Gopher protocol was a (difficult) lesson in the fragility of communication.

While RFC 1436 seemed straightforward and chalk full of information, my team found that the ambiguity in the specifications presented the greatest challenge. Our initial server implementation assumed a specific interpretation of file paths that caused interoperability failures when interacting with other students' clients. Our brittle implementation was fundamentally caused by an excess of intelligence between endpoints and a lack of intelligence at endpoints.

The DNS project also illustrated this layer's critical role in usability. Even though it utilizes low level routing, DNS is an Application Layer protocol. It is the software that translates human intent into network reality. We interact with [google.com](https://www.google.com) but the network requires 142.250.190.142. This hierarchical naming system bridges the gap between human cognition and machine addressing. Additionally, my analysis of the top 500 domains revealed that this layer does much more than simply translation, it makes intelligent decisions. I found that 34% of the sites returned different IP addresses based on where a resolver is located. This shows that CDNs use Application Layer logic to direct users to the closest server, optimizing our interactions with the world before a single packet of content is exchanged.

So, how does the structure and implementation of computer networks impact how we interact with the world? First and foremost, it abstracts complexity to enable usability. Each layer of the internet hides the chaos of the one below it; when I open a web browser, I do not see the TCP retransmissions fixing my spotty Wi-Fi, nor do I observe BGP rerouting my traffic around an outage in Chicago. This implementation provides a potent abstraction, allowing users to interact with the world without managing infrastructure. However, this same structure also defines the strict boundaries of our access. As I found with the firewalls blocking my ICMP probes in Chile and South Africa, network administrators can render an institution invisible to probing tools while keeping them connected, effectively filtering our interactions through policies defined by organizations. This level of control is further amplified by the corporate interests that now govern the network's topology. The rise of hyperscalers demonstrates how massive corporations can physically flatten the network to serve their own latency needs, creating a monoculture that consolidates the internet's power into just a few hands. Yet, even amidst this centralization, the fundamental architecture prioritizes resilience over efficiency. The network of networks structure I explored in the Routing project shows that the internet is built for survival, not just speed; the existence of 17 paths to a single server ensures our interactions remain robust against failure, even if that means taking a slightly longer route.

In conclusion, the structure of the internet is not just a pipe from source to destination. It is a complex decision making system that negotiates physics, corporate dominance, reliability, and language to make our digital interactions possible. My journey through these projects has shown me that every click relies on a miraculous coordination of these layers, functioning in tandem to turn a fragile, commercially-owned web of cables into a global conversation.