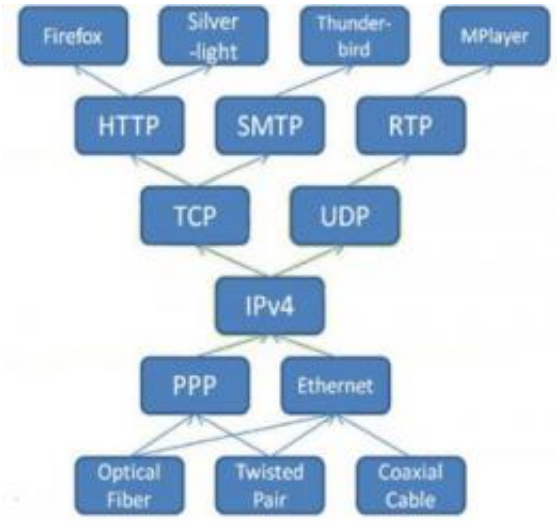
How the Internet architecture got its hourglass shape and what that means for the future

August 15 2011



This illustration of the hourglass Internet architecture shows the six layers, from top to bottom: specific applications, application protocols, transport protocols, network protocols, data-link protocols and physical layer protocols. Credit: (Credit: Constantine Dovrolis)

In the natural world, species that share the same ecosystem often compete for resources, resulting in the extinction of weaker competitors. A new computer model that describes the evolution of the Internet's architecture suggests something similar has happened among the layers of protocols that have survived -- and become extinct -- on the worldwide network.

Understanding this evolutionary process may help computer scientists as they develop protocols to help the Internet accommodate new uses and protect it from a wide range of threats. But the model suggests that unless the new Internet avoids such competition, it will evolve an hourglass shape much like today's Internet.

"To avoid the ossification effects we experience today in the network and transport layers of the Internet, architects of the future Internet need to increase the number of protocols in these middle layers, rather than just push these one- or two-protocol layers to a higher level in the architecture," said Constantine Dovrolis, an associate professor in the School of Computer Science at the Georgia Institute of Technology.

The research will be presented on August 17, 2011 at SIGCOMM, the annual conference of the Special Interest Group on Data Communication , a special interest group of the Association for Computing Machinery. This research was supported by the National Science Foundation.

From top to bottom, the Internet architecture consists of six layers:

• Specific applications, such as Firefox;
• Application protocols, such as Hypertext Transfer Protocol (HTTP);
• Transport protocols, such as Transmission Control Protocol (TCP);
• Network protocols, such as Internet Protocol (IP);
• Data-link protocols, such as Ethernet; and
• Physical layer protocols, such as DSL.

Layers near the top and bottom contain many items, called protocols, while the middle layers do not. The central transport layer contains two protocols and the network layer contains only one, creating an hourglass architecture.

Dovrolis and graduate student Saamer Akhshabi created an evolutionary

model called EvoArch to study the emergence of the Internet's hourglass structure. In the model, the architecture of the network changed with time as new protocols were created at different layers and existing protocols were removed as a result of competition with other protocols in the same layer.

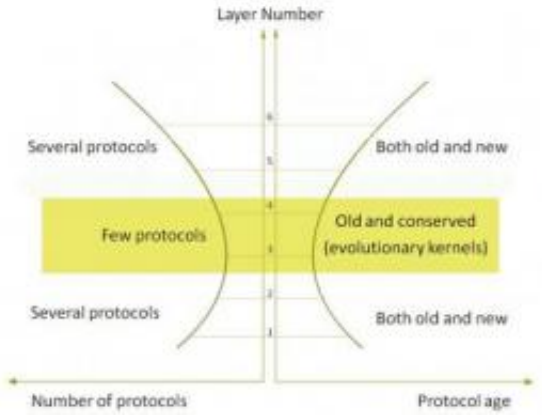


Illustration showing the number and age of protocols in each layer of the Internet architecture. In the middle layers, there are only a few protocols that are old and conserved. Credit: (Credit: Constantine Dovrolis)

EvoArch showed that even if future Internet architectures are not built in the shape of an hourglass initially, they will probably acquire that shape as they evolve. Through their simulations, Dovrolis and Akhshabi found that while the accuracy of the structure improved with time, the basic hourglass shape was always formed -- no matter what shape it started in.

"Even though EvoArch does not capture many practical aspects and protocol-specific or layer-specific details of the Internet architecture, the few parameters it is based on -- the generality of protocols at different layers, the competition between protocols at the same layer, and how new protocols are created -- reproduced the observed hourglass structure

and provided for a robust model," said Dovrolis.

The model revealed a plausible explanation for the Internet's hourglass shape. At the top, protocols are so specialized and selective in what underlying building blocks they use that they rarely compete with each other. When there is very little competition, the probability of extinction for a protocol is close to zero.

"In the top layers of the Internet, many new applications and application-specific protocols are created over time, but few things die, causing the top of the hourglass to get wider over time," said Dovrolis.

In the higher layers, a new protocol can compete and replace an incumbent only if they provide very similar services. For example, services provided by the File Transfer Protocol (FTP) and HTTP overlapped in the application-specific layer. When HTTP became more valuable because of its own higher layer products -- applications such as web browsers -- FTP became extinct.

At the bottom, each protocol serves as a general building block and shares many products in the layer above. For example, the Ethernet protocol in the data-link layer uses the coaxial cable, twisted pair and optical fiber technologies in the physical layer. But because the bottom layer protocols are used in an abundant way, none of them dominate, leading to a low probability of extinction at layers close to the bottom.

The EvoArch model predicts the emergence of few powerful and old protocols in the middle layers, referred to as evolutionary kernels. The evolutionary kernels of the Internet architecture include IPv4 in the network layer, and TCP and the User Datagram Protocol (UDP) in the transport layer. These protocols provide a stable framework through which an always-expanding set of physical and data-link layer protocols, as well as new applications and services at the higher layers, can

interoperate and grow. At the same time, however, those three kernel protocols have been difficult to replace, or even modify significantly.

To ensure more diversity in the middle layers, EvoArch suggests designing protocols that are largely non-overlapping in terms of services and functionality so that they do not compete with each other. The model suggests that protocols overlapping more than 70 percent of their functions start competing with each other.

When the researchers extended the EvoArch model to include a protocol quality factor -- which can capture protocol performance, extent of deployment, reliability or security -- the network grew at a slower pace, but continued to exhibit an hourglass shape. In contrast to the basic model, the quality factor affected the competition in the bottom layers and only high-quality protocols survived there. The model also showed that the kernel protocols in the waist of the hourglass were not necessarily the highest-quality protocols.

"It is not true that the best protocols always win the competition," noted Dovrolis. "Often, the kernels of the architecture are lower-quality protocols that were created early and with just the right set of connections."

Researchers are also using the EvoArch model to explore the emergence of hourglass architectures in other areas, such as metabolic and gene regulatory networks, the organization of the innate immune system, and in gene expression during development.

"I believe there are similarities between the evolution of Internet protocol stacks and the evolution of some biological, technological and social systems, and we are currently using EvoArch to explore these other hourglass structures," said Dovrolis.