Macroscopically Sustainable Networking: On Internet Quines

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ABSTRACT

The Internet stands atop an unseen industrial system required for its continued growth, operation, and maintenance. Its scale could not have been achieved without this reliance, and its dependencies—ranging from sophisticated manufacturing facilities to limited raw materials—make it vulnerable to supply-chain disruptions, which are more likely as human society faces global ecological limits. We introduce the concept of an *Internet quine*, a metaphor that represents a collection of devices, protocols, manufacturing facilities, software tools, and other related components that is self-bootstrapping and capable of being used (by engineers or autonomously) to reproduce itself and all the needed components of the Internet. In this paper, we study the nature of Internet quines and discuss how they could be built. We also attempt to identify a collection of such tools and facilities, and how small and inexpensive they can be made.

CCS Concepts

•**Networks** → *Network components;* •**Hardware** → *Communication hardware, interfaces and storage;*

Keywords

Sustainability; life-cycle analysis

1. INTRODUCTION

The Internet is arguably the largest and most successful technological system humanity has ever created. It is composed of a complex array of hardware and software assembled around the world with materials, energy, skills, and designs also from a global resource base. The fact that the Internet has spread to all regions of the world despite this complexity is a testament to its tremendous utility and the ingenuity of those involved in the design, manufacture, distribution, and operation of its constituent components.

With this complexity comes vulnerability to threats: disruptions in global supply chains, energy shortages, societal instability, and government intervention into its operation. The last two decades have been relatively placid compared with the previous eight or previous eighty, and have provided an environment in which the Internet has been able to grow at a phenomenal pace. Political instability—resulting in the shutdown of the Internet for whole nations—in the last several years has dramatically demonstrated the fragility of the Internet on a regional scale. The effects of widespread climate change and energy limits are predicted to have significant impacts on the global economy, in turn threatening to the disrupt global supply chains upon which the Internet depends [19].

Achieving structural resilience against such challenges, be they at a global, regional, or national scale, calls for a set of networking technologies and components that do not carry such heavy external dependencies and that are truly sustainable [14]. For lack of a better term, we call such a set of technologies required to create a self-sustainable Internet an *Internet quine*, and in this paper explore how to build an Internet quine.[1] In particular, we consider quines with minimal dependencies, adopting as much as possible the principles of "appropriate technology" [9, 21], namely an Internet quine that is a) simple, b) locally reproducible, c) composed of local materials and resources, d) easily repairable, e) affordable, and f) easily recyclable.

Such a quine would have a variety of useful applications. In resource-constrained environments (such as parts of the so-called developing world, or in areas isolated by natural disasters), a functional Internet quine could ensure a link to the rest of the world. It could also serve as the basis for a non-government controlled communications infrastructure for people living under an authoritarian regime that practices widespread censorship. The process of building an Internet quine could also have great pedagogical value, allowing students to "build the Internet from scratch." Moreover, many of the objectives we explore are part of the networking canon: we aim to build networks that are scalable and can be started and tested at a small scale with modest resources, modular networks separated into distinct elements that can be replaced at different scales and technological levels, networks that remain useful under changing conditions and respond to pressures, and open networks that do not require certain systems or components to function.

What an Internet quine would look like is highly dependent on the particular context in which it would be used. As such, we do not propose a single way forward, but weigh what knowledge and resources can be assumed to exist outside the quine and what services it must support. Specifying an Internet quine in its entirety is difficult, as the scale of the Internet and its constituent systems is vast. In this paper we focus on a more tractable goal, that of exploring the manufacturing and operational dependencies of supporting a common use case of the Internet today: end to end communi-

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[1] A *quine* is a computer program that outputs its own source code; metaphorically, an *Internet quine* is an Internet composed of systems that can reproduce that whole Internet.

cation over long distances. We then consider possible alternative architectures for supporting this use case. Our hope is to provide a small nudge towards sustainability.

2. RELATED WORK

The goal of an self-sufficient Internet of the sort we study here is not a new one. In a broader sense, its roots date to the work of the economist E.F. Schumacher, who introduced the concept of *intermediate technology*, now known as *appropriate technology*—technology that is appropriate for a region rather than being created as a global commodity [21]. Schumacher's idea of appropriate technology is one that we might well heed today as we face ecological limits. Similarly, the structure, and downsides, of a complex system (such as the Internet) that embodies a mix of technological and human elements was studied by historian of technology Lewis Mumford throughout the 20th century [11, 12].

More recently, a range of scientists and engineers, from ecologists to computer scientists, have explored building sets of self-sufficient machines. The Open Source Ecology project aims to provide a complete set of designs for appropriate technology that meets all basic human needs [13]; among their tools are several means of manufacturing, including a 3D printer, RepRap [20]. There are numerous 3D printer projects that are capable of self-manufacture but all still require significant material inputs. The Fablab project has similar abilities and ambitions and has aided in setting up networks in Afghanistan [5].

Many of these efforts stem from the ICTD community, which has also studied many of the issues we consider here. Since resource-limited environments break design assumptions that the Internet's infrastructure relies upon, they complicate the deployment and evaluation of networked systems [4]. Understanding the challenges that a network's economic, technical, and social contexts presents is essential for achieving its long-term sustainable operation [3, 8, 23]. Such an understanding of the present Internet infrastructure is surprisingly difficult to come by, further motivating our current study.

Finally, while our focus here is on the Internet's infrastructure, work on the Internet's *architecture* is important to consider in parallel. The Internet's architecture subtly influences all aspects of its physical and operational footprint, and the economic and technological choices that are made every day in its operation. Alternative Internet architectures that enable greater flexibility could prove to simplify the task of developing an Internet quine by removing strict dependency relationships and by enabling interoperability of a more diverse range of network stacks [7, 10, 17, 18].

3. DISASSEMBLY

There are few panoramic analyses of the Internet and its dependencies—specifically material dependencies—in the research literature, and as a result our first task is to virtually disassemble the Internet to understand its constituent parts and needs. We focus on material dependencies as they are more likely to be affected by ecological limits. For simplicity, we study the Internet's dependencies hierarchically, where each component or manufacturing process depends upon components, processes, or materials. We also know that any such analysis is incomplete, as is the one we include here. However, even a crude analysis can help us identify opportunities for sustainability and building an Internet quine.

3.1 Use case

Before we can analyze the Internet's dependencies, we must first begin with a more basic question: what is the set of actions and uses that define the Internet? The Internet has myriad uses and thus it is difficult to say which of these uses is most intrinsic or essential. For concreteness, here we consider the use case of end-to-end communication between two Internet users who are geographically distant. We assume that the components they use are standard—the routers, data centers, transmission systems, operating systems, and so forth that are in use today. Curiously, though the example we begin with is simple, upon study of its dependencies we uncover a great deal of complexity and interdependence. At the outset, we note that in piecemeal this analysis has been done by many in the research literature and industry, but to our knowledge a semi-comprehensive picture of the Internet's dependencies has never been painted.

3.2 Dependencies

We depict the dependencies of the various components of the Internet beginning from our use case in Figure 1. Each box denotes an abstract or concrete component, resource, or function of the Internet or one of its recursive dependencies. Arrows denote dependency; dashed arrows denote optional dependency—that is, a "one of these" relationship. Moving down the chart, we quickly traverse the abstract layers—which represent functional elements that we recognize as central to the Internet (such as routers)—and on to the lower layers which reside in the realm of hardware. As the Internet currently uses the latest IC manufacturing and fiber optics, we consider the consequent dependencies of those technologies and related processes. Once we move beyond hardware manufacturing we enter the realm of chemical compounds and natural resources that are required for many of the relevant manufacturing processes, from making optical fiber to printing circuit boards. We terminate with special nodes that represent ores or otherwise naturally occurring resources.

We do not depict operational or deployment dependencies since they tend to involve a small number of processes—notably, power generation and transportation—which ultimately have to do with energy technologies and resources. These dependencies are very important as energy will be a significant global challenge this century. In addition, we do not depict knowledge or informational dependencies; we discuss the importance of these later.

3.3 Why consider these dependencies?

At first glance the dependencies we find take us far afield of what we traditionally think of as networking. As a result, it raises a natural question: why consider such esoteric and deeply embedded dependencies of the Internet? After all, in one view, the resources we build upon and the dependencies we consider are commodities, and the problems of sourcing the inputs for these are the responsibilities of their respective designers and manufacturers.

We argue that this is not the case and that networking is unique in that it has yielded a system—the Internet—that is far greater than the sum of its parts. Were some specific peripheral or piece of hardware to become unavailable due to dependency failure, the world would scarcely notice unless it were to affect the functioning of the Internet in a material way. While in this paper we do not consider the process by which such dependency failures could occur, knowing what they are down to irreducible roots gives us the ability to secure the whole by divesting from the parts.

3.4 Where do components come from?

Where the dependencies come from is just as important as what they are. Once again, the idea of global commodities and international trade are so firmly entrenched in our thinking today that we take for granted that a resource in another country can be tapped if the price or force is right. However, this is a modern notion—one whose history is scarcely four decades old—and the increasing cost

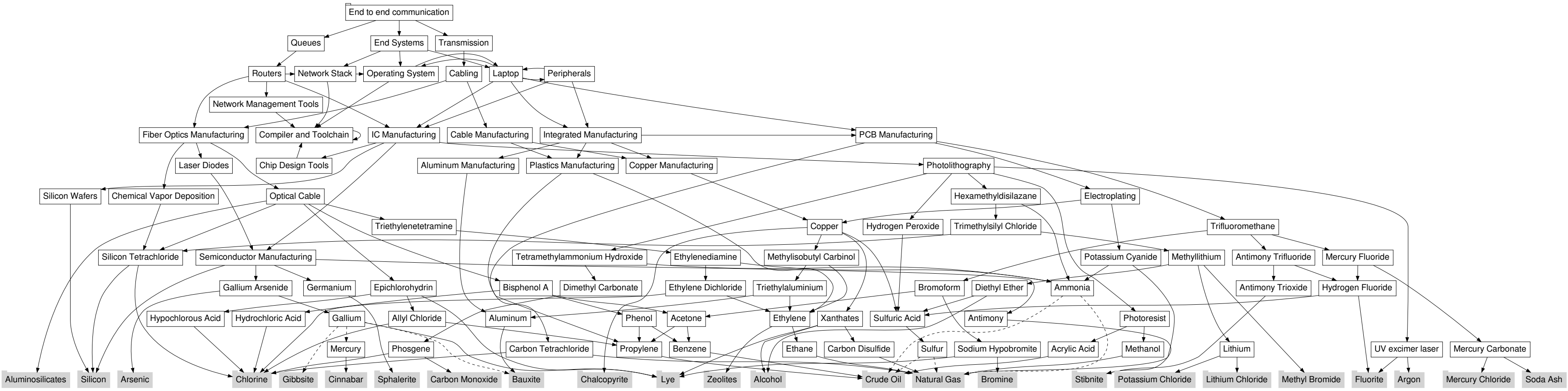

Figure 1: Dependencies of the end-to-end communication use case.

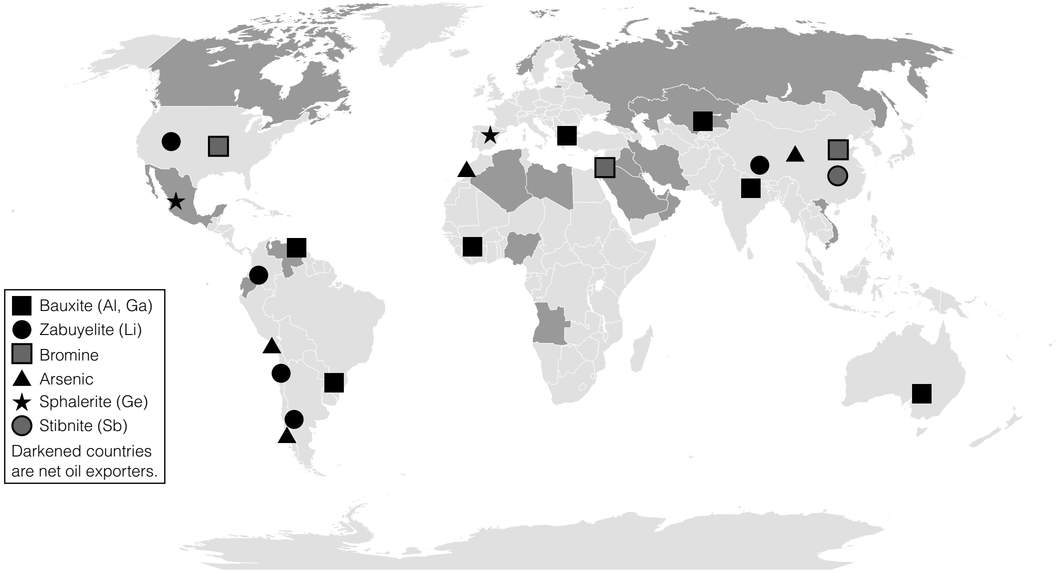

Figure 2: Locations of necessary natural resources.

of energy and increased resource competition might complicate the picture increasingly in the decades to come.[2]

Thus we consider the geographic locations from which the root nodes in our dependency analysis are typically sourced. In all, we found that our simple Internet use case depends upon over a dozen natural resources sourced from numerous countries, as seen in Figure 2. While some resources are both abundant and widespread, key resources are not. Bauxite, for instance, a principal ore for aluminum and rare metals such as gallium (an important semiconductor), is found in sizeable deposits only in Australia, Brazil, Kazakhstan, and Venezuela, with smaller deposits in West Africa and the Balkans.

4. REASSEMBLY

So far we have identified the deep dependencies of the Internet. In doing so, we are reminded of the numerous material resources and manufacturing processes that the Internet requires today, many of which most networking researchers would scarcely recognize, let alone understand. While this was for just one use case, we believe that it covers the preponderance of important Internet use cases and their dependencies.

In this section we consider "reassembly" of the constituent components of the Internet, and would like to shrink the dependency set as we design an Internet quine. At the outset, we note that the entire global industrial system is an Internet quine, just not a very compact one; our goal is to identify a smaller Internet quine. Our goal in this process is to design for self-sufficiency by directly attacking points of interdependence. Specifically, three types of dependency alterations enable moving the dependency graph towards a more minimal set:

- **Replacement.** We can replace an input with another one that provides equivalent functionality.
- **Removal.** We can eliminate a dependency that is no longer valid or required.
- **Multiplicity.** We can add extra options to turn a strict dependency into a choice among multiple optional inputs.

In this section we consider each of these options in turn and together as we explore how to build a more minimal Internet quine. We note that it is crucial that we did not omit dependencies in our analysis as this would lead us to falsely believe that some hypothetical Internet quine achieves self-sufficiency when it in fact does not.

How do we design for self-sufficiency given our knowledge of dependencies? An ideal approach would be to eliminate dependencies as high up in the dependency hierarchy as possible—either through replacement or removal—as this enables us to replace a whole subtree of dependencies at once. However, it is often the case that replacements at higher levels of abstraction do not necessarily provide equivalent functionality. We consider this and discuss the inherent tradeoffs that might have to be made when designing for self-sufficiency. This necessarily raises the complex issue of "what is the set of essential functions and/or guarantees of the Internet?" We address this next.

Finally, we must consider in advance the difficulty that we will have in eliminating dependencies given the root dependency of much of modern networking technology: IC manufacturing. We consider addressing this challenge in two ways. First, we go directly at the problem and consider what series of replacements can entirely eliminate a dependency upon IC manufacturing. Second, we go around the problem by introducing an extra type of input to our dependency graph: salvaged components.

4.1 Core Internet Functionality

Given the complex dependency graph for supporting our use case in the current Internet, is it possible to construct an Internet-like system that will both support the use case and have a simple dependency graph? Point-to-point communication between two geographically distant parties does not fundamentally carry a large set of dependencies. Trivially, such a use case could be satisfied by a physical messenger. Indeed, trained pigeons once carried out this task; a modern variant that implements a delay-tolerant network might include birds with microSD cards strapped to their legs, which in a recent instance proved more efficient than using conventional network infrastructure [1]. Large-scale communication networks existed before many of the technologies used in the current Internet were developed as well, so clearly the set of dependencies we describe above is not strictly necessary to achieve our goal.

For the purposes of our discussion, we consider the primary service that the Internet provides to be routing datagrams between independent administrative domains for automated processing at endpoints. We require only *functional equivalence*, not interoperability, with the existing Internet. In addition, such a network should provide a service interface that is sufficiently generic for multiple application-level services to use it: the system should support layering of protocols and protocol diversity across domains [17, 18], and should not enable only a particular class of applications (assuming the network is capable of meeting an application's performance requirements; inability to stream high-definition video does not prevent a system from meeting our definition). While the postal system meets many of these requirements and coupled with storage media provides functional equivalence, ideally we would also maintain an additional function: near real-time communication.

In addition to defining the minimum services an Internet quine must provide, we must also define what we mean by self-sufficiency. A minimal Internet quine is one that achieves our definition of an Internet-like system, as well as any application-level requirements, while requiring as few resources as possible for its construction and sustainable operation. What resources are available, and what the application-level requirements of the system are, will of course vary depending on the context in which the quine exists. Since the global industrial system was developed over the course of a few hundred years using solely raw resources, in theory those resources and the knowledge required to build all the needed systems for the Internet could replicate it. However, here we do not consider quines on this timescale. We require that the resources in question be locally plentiful for some long period of time, but how long this duration must be leads to different designs. The resources for an Internet quine need not be what we would consider "natural resources" if this duration is fairly short (on the order of a few decades). If the duration is longer then any non-renewable input cannot be depended upon. Indeed, the quine we consider next uses a large supply of salvaged parts.

4.2 A Salvage Internet

One way to reduce the set of dependencies would be to create a networking infrastructure from only salvaged hardware, thus *replacing* many of the dependencies in Figure 1 with premanufactured, but widely available, components. Thanks to the proliferation of current computing technologies, such equipment is widely available in many places, including still-functional equipment which has been discarded and is no longer in use. More-

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[2] Consider, for example, actions by China to control its domestic supply of rare-earth elements [2].

over, local expertise for extending the useful life of computers, cell phones, and other devices already exists in many places. Not only does re-using and re-purposing existing equipment avoid the need for most manufacturing, it also dramatically reduces transportation needs, as most equipment can be found locally.

For our example use case, the salvage requirements are surprisingly modest. Commodity 802.11 WiFi equipment, running open-source drivers and management software, has been successfully used to establish radio links hundreds of kilometers in length, even in very resource-poor environments [15]. Thus we can replace the router node of our dependency graph with such software-based WiFi routers, eliminate cabling, and replace peripherals and laptops with salvaged devices. Assuming access to a working 802.11 radio, the necessary antennas can be fabricated easily by unskilled labor from sheet metal, another common salvage material. Working computers are plentiful worldwide, with a vibrant repair market already in existence. Many cellular phones, the single most widely deployed communications technology in the world, have WiFi capabilities as well, making integration with such a system trivial. Indeed, the power needs of this Internet quine could be satisfied using the same power infrastructure currently used to recharge cellular phones. With this equipment, one could easily imagine a multihop network (though perhaps a low-throughput one) transmitting data across considerable distances.

This Internet quine can be constructed using only common, locally available components; as such, it carries a much simpler set of dependencies. It would also be directly interoperable with the existing Internet. However, it cannot be sustained in the long-term.

4.3 Low-tech Internet

A salvage Internet, while having substantially fewer dependencies than the current Internet infrastructure, still makes significant assumptions about physical resources available outside the quine: namely, a surplus of working or repairable computing equipment that could be repurposed for use as a communications infrastructure. Clearly, this assumption may not always hold, nor could it be sustained in the long-term.

The fundamental challenge we encounter when no longer using salvage is the replacement of integrated circuits. As our dependency analysis shows, the set of dependencies and processes is significantly complicated by IC manufacturing and the fabrication techniques modern ICs require, such as photolithography. Manufacturing radios from simple components using older technology is nothing new. Amateur radio has a long history of utilizing operator ingenuity to create sophisticated communications systems using components and manufacturing techniques that are accessible to hobbyists. Manuals describe how to design and construct fully-working radios using no ICs [6], so neither have the knowledge nor the resources for pre-IC long-distance communication been lost. In such a design, these low-tech radios would provide essentially the backhaul that 802.11 provided in our previous design. We imagine that local networks could still be composed using physical cabling using copper. It is unclear, however, what the end hosts would be or look like in this scenario. Clearly a pre-IC computer, either mechanical or using tubes, could be designed to interface with this low-tech Internet, but these options are far more degenerate than desirable.

4.4 Radical Alternatives

Internet over Avian Carrier. While using birds to communicate over long distances may seem ridiculous in our era, the throughput of such a system could actually be quite high, with trained birds with tiny storage devices strapped to their legs [1]. While this would eliminate a substantial number of manufacturing processes that enable long-distance wired or wireless communication, the technology for making and reading storage devices would remain. In addition, network applications would have to be designed to be delay tolerant.

An IC-free Internet Core. ICs are central to all computing technology and are thus one of the primary bottlenecks for creating an Internet quine. We could envision a core routing infrastructure that is IC-free if we were to design systems that used entirely optical circuit switching or even mechanical electrical circuit switches. The signaling infrastructure would be radically different from the Internet as it exists today, and we would lose the benefits of statistical multiplexing, but would eliminate the need for ICs for the core.

Old manufacturing. Could we use 1950s technology and/or some simpler but less efficient manufacturing processes to substitute at different layers than salvage in the dependency chart? It seems likely that today's knowledge combined with manufacturing techniques of the 1950s could yield a working Internet; the challenge then is to map the dependencies of the 1950s technologies that would be used and verify that they are indeed significantly smaller than today's.

Printable and Organic Circuits. New research into printable and organic circuits may enable the manufacturing of circuits for networking hardware with a vastly different set of material dependencies that eventually could be bioregionally produced [22, 24]. While these circuits currently are far slower than conventional ICs, it is possible that both the speed and complexity of these techniques will be improved soon enough that they can be leveraged in low-resource environments to manufacture many of the components needed for an Internet quine.

5. CONCLUSIONS

Our dependency analysis reveals several interesting properties about the nature of both the Internet's present physical infrastructure as well as its architecture. It also provides us a reminder of the inherent value in reducing the Internet's dependencies.

5.1 Lessons

Since our foray into this subject is preliminary, we do not offer any deep lessons. Nevertheless, we have not seen any prior analyses like the one we present in this paper, and as such offer a few general observations.

The Internet is highly dependent. Most obviously, we observe that the present Internet is heavily dependent on many industries not typically associated with network equipment. In particular, several of these dependencies include processes which rely on limited natural resources. Many others require highly-skilled workers and specialized manufacturing processes. This situation is ironic given the Internet's widespread and deserved reputation as a remarkably resilient system [16]. It achieves this resilience from a functionality perspective by ensuring that failed links do not break the entire system: traffic can easily be routed through substitute paths in these events. From a structural perspective, however, substituting for a failed dependency is extremely difficult.

We also note that many of the dependencies we identified have no clear alternative that can meet the performance demands of the current Internet. For example, physical limitations make fiber-optic cables the only transport medium that can satisfy today's requirements for data volume and transmission distance. As a result, disruptions in the availability of these dependencies will require users to adjust their expectations about the Internet's performance characteristics.

Fundamental dependencies are limited. We can provide a reasonable equivalent to the basic service model of the Internet with substantially fewer resource dependencies than needed today. In this sense, the infrastructure of the Internet itself does not *inherently* require the complex dependency graph shown in Figure 1. Given appropriate performance expectations, an Internet quine may be very small, requiring only resources that are both plentiful and widely distributed.

Information is a cheap resource. Information is the cheapest commodity on the Internet. As a result, any opportunities to substitute physical resource dependencies with information-based dependencies can dramatically simplify the dependency graph. In general, we can decrease the size of an Internet quine by substituting information resources for specialized dependencies, such as a protocol that obviates a significant piece of infrastructure. Where this is not possible, general purpose tools should be favored over special purpose machines. Here we use the definition of tool and machine due to Mumford [11]: the user of a tool imparts the tool's purpose and role, whereas those qualities of a machine are typically statically determined in its design. Relying on users' knowledge to operate general purpose tools, rather than on purpose-built machines, can simplify an Internet quine's dependency graph. Such tools can serve multiple roles in the dependency graph, and likely have fewer, simpler dependencies themselves.

5.2 Benefits of Simplicity

We have already explored the primary benefit of simplicity: building a (more minimal) Internet quine. Independently, it also has two other benefits.

Networking education. Networking as it is taught today is parochial. Those instructors who are interested in systems discuss the distributed systems that compose the Internet; others discuss the network architecture and how and why it makes sense; others still examine it using the language of queueing theory. These strands of networking pedagogy all have their place and contribute to our understanding, but they do not connect with the real world—the operation of a real-world system. In part, this is because it is difficult to teach the entirety of a system as complex as the Internet in a single course. However, an Internet quine could be sourced and built from scratch for pedagogical purposes. This could be a valuable undergraduate course or course series: "Building the Internet from Scratch." While universities with large engineering departments likely already have many of the resources needed today, almost all have the resources for a salvage Internet.

Inching towards sustainability. In decreasing the resource base required to achieve the Internet's functionality, there is a good chance we also increase the Internet's sustainability in every sense of the word. That is, an Internet whose functionality can be replicated independently in many places is one that will not stop functioning due to a single common-cause failure or depletion of a key natural resource. Similarly, as a result of decreasing the complexity of the Internet's requirements, it is possible (though difficult to verify) that the components yielded are more environmentally sustainable, in that they either re-use or do without components that would have otherwise been manufactured anew.

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