Tollbooth Civilization:
Why the Work That Becomes Foundational Cannot Be Owned,
and What Gets Owned Instead

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Abstract

Rankings of private wealth are read as rankings of contribution to civilization, and the reading is wrong in a way that has structure. Work becomes foundational by becoming non-excludable, standardized, cheap to copy, and depended upon by everything above it, and each of those properties is what stops its creator from charging for it. The people whose work became the substrate of modern technology, the designers of the internet's transport protocol, the metal-oxide-semiconductor transistor, the small public-domain database inside most devices, the salt-and-sugar formula that rehydrates a dying child, captured almost none of the value their work carries, and they captured almost none of it because the work became foundational. This paper models a technological civilization as a stack of serially dependent layers, each able to levy a per-use toll, and computes what tolls do to it. In a normalized market the open, untolled stack delivers social value 0.5 and its creators keep nothing; a single owner of the whole stack keeps 0.25 while halving throughput; and when the stack is split among independent tollbooths the tolls compound, so that two booths set a higher combined price than one owner would and collect less between them while users are worse off, and twenty booths cut throughput to about 5 percent of the open level. The sustainable private capture of any one foundational layer falls as $1/(2N)$ in the number of complementary layers, so the model's capturable fraction reaches the roughly 2.2 percent of social surplus that Nordhaus estimated innovators actually capture near a stack 23 layers deep. The configuration that maximizes social value is the one in which creators capture nothing. Great fortunes form instead at the narrower, more excludable layers above the commons, where control over a point that use must pass through can be turned into recurring revenue, and ownership of such a point is then narrated as though it were the building of the road beneath it. The paper is careful about what this does and does not license: appropriability drives real invention, integration and scaling are real work, and a single integrated owner does less damage than a fragmented anticommons. The claim is the systematic divergence between contribution and capture, and the mistaking of the tollbooth for the road.

Cerf's Missing Invoice

In 1974 Vint Cerf and Robert Kahn published a design for moving data between networks that knew nothing of one another, and they charged nothing for it (Cerf & Kahn, 1974). Suppose they had done what an owner ordinarily does and attached a toll, a hundredth of a cent, 10^{-4} dollars, to each packet crossing the boundary their protocol defined. Their revenue would be that toll times the number of packets. Nobody can audit the number, but the internet has carried something on the order of 10^{18} to 10^{19} packets, and a hundredth of a cent on 10^{19} is 10^{15} dollars. The two of them would have been the world's first quadrillionaires, and the meter would still be running.

The number is ridiculous, and the ridiculousness is the whole problem in miniature. A per-packet toll high enough to make Cerf rich would have made the internet not worth building. Every device that speaks the protocol speaks it because adopting it costs nothing and asks no one's permission. Put a turnstile at the boundary and the traffic reroutes around it, or never forms. The value of TCP and the impossibility of charging for TCP are the same fact seen from two sides. The protocol

became worth an unimaginable amount by becoming something no one had to pay to use.

This is the pattern the paper is about. The metal-oxide-semiconductor field-effect transistor, demonstrated at Bell Labs in 1959 by Mohamed Atalla and Dawon Kahng, is the switching element of essentially all digital electronics; the Computer History Museum calls the MOS transistor the most frequently manufactured object in human history, with cumulative production around 10^{22} devices. SQLite, written and placed in the public domain by D. Richard Hipp, sits inside most phones, most browsers, and, by its authors' own count, over a trillion active databases. Oral rehydration therapy is water, salt, and sugar in the proportions that the coupled transport of sodium and glucose across the gut wall makes effective; The Lancet, in 1978, judged the underlying discovery potentially the most important medical advance of the century, and no fortune has ever been built on telling a mother the correct ratio. The people who made these things are, by the ordinary measure, not rich. The ordinary measure is the thing to interrogate.

A wealth ranking sorts people by the market value of the claims they own. That value tracks how much revenue a claim can be made to yield, which tracks how effectively others can be excluded from what the claim controls, which has almost nothing to do with how much the underlying thing contributed to anyone's life. Nordhaus (2004) measured the gap directly. Estimating the share of the social surplus from technological advance that its producers manage to keep, for the United States nonfarm business sector across 1948 to 2001, he found that innovators capture about 2.2 percent, the remaining surplus flowing to consumers and to later producers who build on the advance. His abstract calls the captured share a minuscule fraction; the body puts a number on it. Read against a Forbes list, the finding is not that innovators are underpaid by a little. The quantity a wealth ranking measures and the quantity it is taken to measure are different quantities, and the second is more than 40 times the first.

Why the Foundational Cannot Charge

The low capture rate is not a market imperfection waiting for a fix. For the most foundational work it is a structural consequence of what foundational means, and the same properties that make a piece of work foundational are the ones that make it uncapturable.

Information is the base case, and Arrow (1962) stated it as a paradox. A piece of technical knowledge is non-rival, so one person's use does not diminish another's, and it is non-excludable once disclosed, because to sell it the seller must reveal it, and once revealed it can be used without further payment. Samuelson (1954) had stated the general form eight years before: a pure public good is one whose consumption by one agent subtracts nothing from its availability to others, and markets left alone underprovide it because no seller can meter what no one can be kept from. Romer (1990) built the growth theory on the same property, treating ideas as non-rival inputs whose free reuse is the engine of long-run growth precisely because their value is not exhausted by the person who first has them. The through-line is old and settled. The more completely a thing has the character of knowledge, the less of the value it generates can be fenced.

Foundational technology inherits the property and sharpens it with three more. It is standard-

ized, which is to say its worth comes from everyone using the same one, and a toll that fragments adoption destroys the standardization that was the source of the worth. It is cheap to replicate, so any price much above zero invites a free substitute, and the substitute need not be better, only unowned. And it is complementary rather than final, delivering its value inside products that thousands of other firms assemble and sell, so the surplus appears on their books and in their customers' lives and never passes a checkout the originator controls. Teece (1986) named the regime this produces. When appropriability is weak, the returns from an innovation flow not to the inventor but to whoever owns the complementary assets it needs to reach a market, the manufacturing, the distribution, the brand, the installed base. The inventor of a widely usable primitive owns none of these by virtue of the invention.

There is a further reason the base of the stack tends to hold no owner, which is that it was frequently built by many hands. Allen (1983) documented collective invention among the ironmasters of the Cleveland district, who published their blast-furnace dimensions and yields to one another and drove a rapid cumulative advance that belonged to no one firm. Much foundational work has this shape. TCP became TCP/IP and then a suite maintained by a standards community; the transistor passed through Bell Labs and a thousand later refinements; a protocol acquires its authority by being implemented independently many times over. When a capability is produced this way, the question of who should capture its value has no clean answer, because a crowd built it.

Two quantities are worth separating, because the whole argument turns on their ratio. Write S_i for the social value a contribution i creates, the amount by which the world is better for it than for its most likely absence, and P_i for the private value its creator can capture. Define the capture ratio and its inverse, which we will call civilizational leverage,

$$\kappa_i \;=\; \frac{P_i}{S_i}, \qquad L_i \;=\; \frac{S_i}{P_i} \;=\; \frac{1}{\kappa_i}.$$

Contribution is the numerator of L_i; appropriation is its denominator. The argument of the previous paragraphs is that for the most foundational work the two are inversely related, so that the same features that raise S_i, non-excludability, standardization, replicability, and complementarity, are the ones that push P_i toward zero. A wealth ranking sorts the world by P_i and is read as though it sorted by S_i. The people with the highest L_i are invisible to it by construction.

The Stack and Its Chokepoints

A technological civilization is a stack of layers that depend on one another in series. Mathematics and measurement and published science sit at the bottom. Above them are the technical primitives, the transistor, the transport protocol, the name system, the clock-synchronization protocol, the compression and cryptographic routines. Above those are shared infrastructures, the grids and networks and fabrication plants and public research institutions. Above those are the platforms and production systems, the operating systems and clouds and design suites and app stores. Near the top are consumer products and brands, and at the very top the financial and narrative layer,

the equity and the story about who made it. Each layer runs on the ones below and is oblivious to most of them.

Two things flow through the stack in opposite directions. Dependency flows down: every layer needs the ones beneath it, and the lower a layer sits the more of the structure above depends on it. Money and recognition flow up: the higher a layer sits the closer it is to a paying customer, a billing relationship, a proprietary account, a capital market, and a name a journalist can attach to the whole. The layer that the most things depend on and the layer that captures the most revenue sit near opposite ends of the same column. Bresnahan and Trajtenberg (1995) gave the lower layers their name, the general-purpose technology, defined by pervasiveness across sectors, continual improvement, and the innovational complementarities that let it seed advances in every field it touches. Generality and appropriability point opposite ways. A technology earns the label by being useful everywhere, which is the same as being ownable nowhere in particular.

A tollbooth forms where a layer can be made both narrow and unavoidable. Narrowness comes from a proprietary format, an interface, a certification, a distribution channel, a payment rail, a store, a standard-essential patent. Unavoidability comes from lock-in. David (1985) drew the mechanism out of the QWERTY keyboard, which persists because everyone else uses it and the cost of coordinating a switch exceeds any one typist's gain, rather than because it is fast. Where a layer combines the two, its owner collects not for producing anything ongoing but for standing astride a point that traffic cannot route around. Christophers (2020) reads the contemporary economy as increasingly organized this way, around the ownership of scarce assets, land, spectrum, intellectual property, platforms, contracts, that yield income from control rather than from making. Giblin and Doctorow (2022) trace the same structure through the creative industries, where a few firms sit in the chokepoint between makers and audiences and squeeze both sides of it. The tollbooth is the chokepoint priced.

The Arithmetic of Tolls

The instinct that a foundational creator ought simply to charge a small fee runs into arithmetic. If a use of the stack requires many layers in series, and each layer's owner sets a toll to maximize that layer's own take, the tolls interact in a way that harms everyone, the owners included. The result is old. In a chapter on producers of complementary goods first published in 1838, Cournot took the case of copper and zinc, each held by a separate monopolist and combined into brass, and showed that the two independent owners set a higher total price, and sell less, than a single owner of both metals would (Cournot, 1897). The accompanying model puts his result on the civilizational stack and reads the numbers off it.

Normalize the market. A unit mass of potential uses, packets or transactions or new products, each with a willingness to pay drawn uniformly on the interval from zero to one, and no cost of provision beyond the tolls, so demand for the stack at total per-use price P is $Q(P) = 1 - P$. Let the stack have N layers in series, each essential, each owned by someone who sets a per-use toll r_i to maximize $r_i\, Q$ taking the others as given. The symmetric equilibrium and the welfare it produces are

$$r_i^\star = \frac{1}{N+1}, \qquad P_N = \frac{N}{N+1}, \qquad Q_N = \frac{1}{N+1}, \qquad W_N = \frac{2N+1}{2(N+1)^2},$$

where W_N sums consumer surplus and total toll revenue. Everything the model says is contained in comparing three ways of owning the same stack.

The open stack tolls nothing. Its throughput is the entire market and its welfare is 0.5, all of it consumer surplus, none of it captured. A single owner of the whole stack sets one price, keeps 0.25, and in doing so cuts throughput to 0.5 and welfare to 0.375; the quarter it captures comes at the cost of an eighth of the surplus destroyed, the ordinary deadweight loss of a monopoly. Fragment that single owner into independent tollbooths and the Cournot interaction appears. Two booths on the same road each charge a third, for a combined price of 0.667, above the 0.5 a single owner would set. Throughput falls to 0.333. Between them the two booths collect 0.222, less than the 0.25 a single owner kept, and consumer surplus falls from 0.125 to 0.056. Splitting one road into two tollbooths makes the users poorer and the owners collectively poorer at the same time. This is the tragedy of the anticommons that Heller and Eisenberg (1998) named in biomedical research, where too many parties holding rights to exclude leave a resource underused because each can block the others; here it appears in price form, as fragmented ownership pricing its own road into disuse.

Deepen the stack and the collapse accelerates. Ten independent tollbooths cut throughput to about 9 percent of the open level; twenty cut it to about 5 percent. Welfare falls with them, to about a sixth of the open value at ten booths and under a tenth at twenty. This is the packet tax made quantitative. Twenty foundational layers each levying an individually trivial toll do not enrich twenty inventors; they strangle the throughput that was the source of all the value, and the strangling worsens with every layer added. Shapiro (2001) described the applied version as the patent thicket, the dense overlap of complementary rights a product must clear before it can ship, and Lemley and Shapiro (2007) named the pricing pathology royalty stacking, the accumulation of individually reasonable royalties into an unpayable sum. The magnitude in real standard-essential-patent disputes is contested, and honestly so, but the direction the model gives is not: independent tolls on complements add up faster than the market can bear.

The same model yields the non-appropriation principle as a limit. Take one foundational layer embedded in a stack of N complements and ask the most its owner can sustainably charge without collapsing adoption. The revenue-maximizing toll on one of N symmetric layers is $r^\star = 1/(2N)$, and the fraction of the throughput surplus that toll captures, crediting the layer with the whole surplus it is a but-for condition for, is

$$\kappa(N) \;=\; \frac{1}{2N} \;\longrightarrow\; 0, \qquad L(N) \;=\; 2N \;\longrightarrow\; \infty \qquad (N \to \infty).$$

The deeper the stack a layer sits beneath, the smaller the share of the value passing through it that its owner can take. At a stack 20 layers deep the sustainable capture of any single foundational layer is about 2.5 percent, a civilizational leverage of 40 to 1. The model's capturable fraction

passes Nordhaus's empirically estimated 2.2 percent near a stack 23 layers deep, which is not a calibration and should not be mistaken for one, though it is a striking place for a stipulated model and a measured economy to meet. Becoming more foundational does not raise what a creator can charge. It lowers it, toward zero.

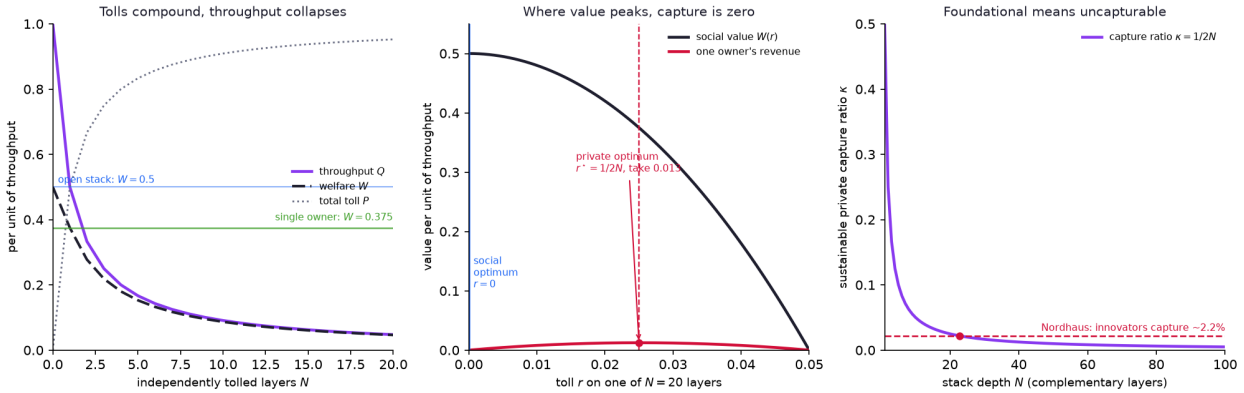

Figure 1: Three readings of the same serially dependent stack. Left, as independent owners toll more of the stack, the total toll P rises toward the choke price while throughput Q and welfare W collapse; two tollbooths already price above the single-owner line at welfare 0.375, and both fall well below the open stack at welfare 0.5. Centre, for one layer embedded in a stack of $N = 20$, social value $W(r)$ is greatest at a zero toll while the layer-owner's own revenue peaks at a strictly positive toll $r^\star = 1/2N$, where even the maximum take is a sliver of the value at stake: the configuration that maximizes social value is the one in which the creator captures nothing. Right, the sustainable capture ratio $\kappa = 1/2N$ falls as the stack deepens, crossing the roughly 2.2 percent of social surplus Nordhaus estimated innovators actually capture near a depth of 23. Every value is a property of the normalized model, not a measurement of any real market.

Two checks keep the model honest. The orderings are not artifacts of the linear demand curve: under the family $Q(P) = (1 - P)^\theta$ the symmetric equilibrium toll has the closed form $r^\star = 1/(N + \theta)$, and both the throughput collapse and the ranking of open above integrated above fragmented hold for every positive θ; across 2,000 seeded draws of the curvature and the market size, every draw preserves both orderings, while the depth of the collapse varies, throughput at ten tolled layers surviving at between about 4 and 18 percent of the open level depending on curvature. And the single integrated owner is a genuine second-best rather than a straw villain. A monopolist owning the entire stack internalizes the complementarity and prices it once, doing strictly less damage than the fragmented anticommons above it. Openness ranks first, integration second, fragmentation last. Any argument that reads this model as proving all ownership illegitimate has misread it.

Owning the Tollbooth, Narrating the Road

The fortunes the stack throws off are real, and they collect at the excludable layers near its top. The interesting move is not the collecting but the telling, the routine conversion of a claim on one layer into authorship of the whole column beneath it.

The mechanism is visible in cases where the public record is unusually complete. NASA's Commercial Orbital Transportation Services program was designed to call a private launch industry into being, paying milestone-based awards, a few hundred million dollars to SpaceX among them, with the agency and its space station as the anchor customer and the accumulated public science of decades as the substrate. SpaceX then did real and difficult engineering, drove launch costs down, and outperformed incumbent contractors on their own terms. Both claims hold. The popular account keeps only the second, resolving a distributed system of public research, public procurement, institutional knowledge, suppliers, workers, and private engineering into the name and personality of the residual equity holder. Mazzucato (2013) assembled the evidence that the state routinely occupies the foundational, risk-absorbing layers of exactly this kind, from the internet's protocols to the components of a smartphone to the frontier of pharmaceutical research, and Mazzucato (2018) put the general name to the operation, the narration of value extraction as value creation. Ownership of a layer is retold as the making of the stack.

The software interface is where the retelling is subtlest, and it deserves precision rather than a slogan. A design-software company does not own geometry, or the calculus, or the numerical methods its product runs on; those sit in the epistemic commons and cannot be fenced. What it can own is the proprietary format in which a firm's accumulated work is stored, the interface others must build against, the account through which collaboration flows. It converts universally available mathematics into a non-portable operational dependency, so that a firm's continued access to its own past work is conditioned on its continued relationship with a vendor. The value captured is the switching cost wrapped around the mathematics, not the mathematics. That the reverse move is possible the same industry shows: Adobe placed the core of the PDF specification into an open international standard, ISO 32000-1, in 2008, and issued a royalty-free patent license for it, making the format more infrastructural by making it less owned, and leaving the proprietary application business to compete above the now-open layer. The layer and the enclosure of the layer are separable, and which one a firm is paid for is the question worth asking.

Rent-seeking supplies the last piece, the cost a wealth ranking cannot see at all. Tullock (1967) observed that the social cost of monopoly is not only the deadweight triangle but the real resources spent acquiring and defending the monopoly position, the lawyers and lobbyists and the effort that competes for a rent instead of producing anything. Krueger (1974) generalized it into the political economy of the rent-seeking society, where control over access, an import license, a spectrum grant, a standard, becomes a prize worth expending real resources to win. The tollbooth economy runs on this expenditure. A large share of what the upper layers spend goes not to building roads but to securing and narrating positions on roads that already exist, and that spending is counted, where it is counted at all, as the cost of creating the value it in fact only captures.

Cases at the Base of the Stack

The pattern survives contact with particular cases, provided the counterfactual is stated carefully. The value of a foundational contribution is not the value of everything built on top of it, which belongs to the builders too, but the value of the acceleration, the cost reduction, the standardization,

and the interoperability it provided over the next-best alternative. Even measured that narrow way the leverage is extreme and the capture near zero.

The transport protocol is the cleanest case. Cerf and Kahn published TCP openly, took no royalty, and shared the 2004 Turing Award for it; the counterfactual is not a world without internetworking but one where it arrived later, more fragmented, and less interoperable, and the value of averting that reached essentially everyone except its authors. The transistor is the largest in magnitude: Atalla and Kahng's surface-passivation work made the MOS transistor manufacturable, and roughly 10^{22} of them later the two names are unknown to the public that carries billions of their descendants in its pockets. SQLite is the purest case of deliberate non-appropriation, with a concentrated author, near-universal deployment, and a public-domain dedication that forecloses capture by design, so that a database inside more devices than any other returns its author a salary and a reputation and nothing that scales with its use. Oral rehydration therapy is the case that most embarrasses the wealth measure: a discovery credited with saving tens of millions of lives, unpatentable because it is a ratio of three cheap substances. The formula costs pennies. On any balance sheet that records ownership it is worth nothing at all.

Open-source software lets the divergence be seen in a single pair of numbers. Hoffmann, Nagle and Zhou (2024) estimated what it would cost to rebuild the freely available software firms depend on, against what firms would have to pay to replace it, and found a supply-side cost near 4.15 billion dollars and a demand-side value near 8.8 trillion, a ratio above a thousand between the value the software delivers and the cost of the labor that produced it. The demand-side figure is a modeled counterfactual and should be read as an estimate, but its shape is the argument: the same code, copied at no cost into ten thousand firms, generates a value that dwarfs its production and accrues to none of its producers. The folk figures point the same way and should be handled with more caution. A number of 15.85 trillion dollars circulates for the lifetime consumer savings from one power-switching device, the insulated-gate bipolar transistor; it comes from a compendium the inventor assembled himself, rests on assumptions such as a 50 percent global penetration of variable-speed drives, and is not an independent measurement. The right use of such a number is not to certify a specific fortune-in-kind but to note that its order of magnitude is unremarkable in this territory, and that the person attached to it captured a rounding error against it.

What the Divergence Licenses

A critique that proves too much proves nothing, and this one has firm boundaries worth stating as plainly as the thesis. The claim is a systematic divergence between contribution and capture, and a habit of narrating control as creation. It is not the claim that all wealth is rent, that appropriation is theft, or that the people at the top of the stack contribute nothing. Each of those would be false, and the model above is part of why.

Appropriability does real work. The prospect of capturing some of an innovation's value is a genuine incentive to produce it, and where imitation is easy and development is expensive, a period of exclusion may be the only thing that funds the development at all. The 2.2 percent Nordhaus measured is small. It is not zero. At the margin it moves invention. The public-goods tradition

from Samuelson through Arrow to Romer treats under-appropriation as an under-provision problem for this reason. A world that drove every capture ratio to zero overnight would have less of the foundational work this paper admires, and the honest position holds two things together: that appropriation incentivizes creation, and that appropriation and creation are nonetheless distinct, and diverge most for the work that matters most.

Integration and scale are real too. Turning a pile of primitives into something a person can buy and rely on is difficult, valuable work, and the firms that do it are not frauds for depending on public and open foundations, since every firm does. Teece's (1986) point cuts both ways here. That the owner of complementary assets captures the value of an innovation is sometimes rent extracted from an inventor and sometimes the just return to the genuinely hard work of manufacturing, distributing, and supporting a thing at scale. The model is equally clear that a single integrated owner is a second-best worth preferring to the anticommons. Nothing here argues for shattering the upper layers into competing tollbooths, which is the disease and not the cure.

What the analysis does license is narrower and sharper. It licenses reading a wealth ranking as a ranking of appropriability and bottleneck control rather than of contribution, and treating the two as the different quantities they are. It licenses skepticism toward any account that resolves a distributed, publicly seeded technological system into a single founder's genius. It licenses a policy preference for keeping foundational layers open, for collecting public returns at the level of the firm or the portfolio rather than as a tax on every use of a primitive, and for refusing to let the second-best of integration be sold as the first-best of creation. And it forbids the one move the tollbooth economy most depends on, the conversion of a position on a road into a claim to have built it.

The Commons Is the Condition, Not the Failure

The economics of information has a long habit of calling non-appropriability a market failure, a place where private incentives fall short of the social optimum and something must be done. On the foundational layers this paper has described, the framing inverts. Non-appropriability there is the condition of the thing working at all.

The model made the inversion exact. The configuration that maximizes the social value of the stack is the open one, where throughput is whole and welfare is 0.5 and the creators capture nothing, and every departure toward capture, whether by one integrated owner or by many independent booths, moves the system strictly downhill from there. Producers keep little of that surplus; the rest, about 98 percent of it, reaches everyone else, which is the only form in which a foundational technology has value at all. A transport protocol that could be metered would not have become the internet; a transistor carrying a per-unit royalty to its inventor would not be manufactured 10^{22} times; a rehydration formula under license would not have reached the children it reached. The uncaptured surplus and the civilization are the same object.

The missing invoice in the first section is therefore not a tragedy to be corrected but the asset itself. Cerf's failure to become a quadrillionaire is the mechanism by which his protocol's value was

delivered, and the reason there is a network worth trying to put a tollbooth on in the first place. A tollbooth civilization is one that has learned to read this backward, to see the toll as the value and the open road as an oversight, to award its largest prizes and its highest status to the layers that charge and its silence to the layers that carry. The cure is not a toll on the carriers; it lies in refusing to mistake the tollbooth for the road, and in remembering, when the next fortune is narrated as an act of creation, that the roads it stands on were mostly built by people who could not, and did not, send anyone a bill.

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