Pricing and Architecture of the Internet: Historical Perspectives from Telecommunications and Transportation

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Abstract. With telecommunications in a slump, the search is on for ways to re-invigorate this key industry. The main problems are clearly economic much more than technological, and many of the proposed remedies would lead to new architectures for the Internet that would provide for greater control by carriers. They would drastically reduce the role of the end-to-end principle, the main foundation for the success of the Internet, in which functionality resides at the edges of the network. The proposals to restrict voice over Internet (VoIP) are just one part of this trend.

Historical precedents from telecommunications for introduction of differentiated services and sophisticated charging methods on the Internet are discouraging. The general trend has been towards decreasing price discrimination and simpler pricing.

The history of transportation presents a different picture, with frequent movements towards increasing price discrimination and more complicated pricing (although with many noteworthy reversals). Charging according to the nature of the goods being transported has been and continues to be the norm. Since the incentives to price discriminate are increasing, and the ability to do so is also growing, it is conceivable that telecommunications might break with its historical record and follow the example of transportation. It is therefore of interest to examine the evolution of pricing and quality differentiation in transportation.

Some historical sketches on the evolution of pricing in transportation are presented. Their implications for telecommunications, and especially for Internet pricing and architecture, are discussed.

1 Introduction

The telecommunications industry at the end of 2003 is perceived to be in a deep slump. A closer examination shows that in spite of many bankruptcies, total revenues of the telecom service sector as a whole are reasonably healthy, having suffered at most a slight decline, following a period of very rapid growth [58, 68]. On the other hand, the telecom supplier sector as well as stock market valuations of almost all telecom enterprises have collapsed, as has the aggregate investment level. This reflects a collapse of expectations that telecom revenues would skyrocket.

There is a concern about the ability of the telecom industry to deploy innovative new services that the recovery of the information technology (IT) industry as a whole may depend on. The problem is that not only is this industry dealing with gross overcapacity in many sectors, but it may not be structured properly for the future. Technology is not the main problem, as it is more than adequate for the demands placed on it, and is still advancing rapidly. It is the economics of future telecom services that is in question. In a memorable phrase attributed to David Clark, "we know how to route packets, what we don't know how to do is route dollars."

In searching for a way out of its slough of despond, the telecommunications industry is considering major changes in the architectures of networks, changes that go counter to recent trends. As an example, in early 2003, a few months after AT&T pioneered a flat-rate domestic long distance calling plan (after resisting valiantly for many years, along with the rest of the industry), followed later by an international flat-rate plan, a high-level manager from AT&T as well as a representative of another service provider talked at an industry meeting about the critical need to bring usage-sensitive pricing to the Internet. Since that time, the flat-rate bandwagon has continued to pick up speed. Sprint started offering in August 2003 a flat-rate plan that includes all types of domestic voice calls, wireless as well as wireline. On the other hand, industry leaders continue calling for new network architectures that would include as a key feature measured rates and have application-aware cores [9]. These desires by industry leaders for new architectures are not just empty dreams. They also affect their day-to-day actions and the evolution of the current network. As one example, peering of VoIP traffic is not progressing much at traditional service providers. The main obstacles are not technical, but economic ones, as carriers are waiting to establish new business models. The industry's desires are reflected in the words of one official carrier representative, who predicted that "[VoIP peering] won't be handled like Internet peering, where we all terminate each other's traffic without paying fees; it's going to follow the voice model" [43]. (In the meantime, independent VoIP service providers are happily growing their business through offerings which manage to ride over the ordinary Internet with its standard peering arrangements.)

How do we reconcile this contrast between what is happening in the marketplace and what is desired by the service providers? The telecom industry could simply be irrational in its attitudes. There has been a trend, going back centuries, of preoccupation with content and undervaluation of connectivity [52], and a persistent lack of understanding of the advantages of simple pricing [51, 53]. Many times the industry was forced against its will into simple pricing or else accidentally stumbled into it, and yet eventually this worked out for the good of the service providers. However, the industry views simple pricing as the disease that has contributed to the current telecom depression. The wireless industry, in particular, has often boasted that it managed to avoid the mistakes of the Internet by avoiding the open architecture and flat-rate pricing of the latter. And indeed, cellular revenues continue to grow, while those of the rest of the industry decline or at best stay constant. The spate of bankruptcies and downsizings that we have witnessed in telecom was most pronounced in the Internet sector, and has largely bypassed wireless. (Of course, there have been giant duds in the wireless arena, as with the 3G spectrum auctions. There have also been major disasters in related areas, in particular in low orbit satellite communications, with Iridium and competitors all going bust. But on the whole, the wireless industry has managed to absorb such disasters without the extreme pain experienced elsewhere in telecommunications.) Cellular today serves more people and has higher revenues than the Internet, both in the U.S. and (even more so) in the rest of the world. Thus it is understandable that the rest of the telecom industry might like to imitate the wireless sector.

Historical precedents in telecommunications argue for continuation of the trend towards simplicity. (See [53]. Section 7 has a brief survey. Note also the early work, dating back to the late 1980s, of Anania and Solomon [3], predicting that flat rates would dominate for data networks.) There have also long been arguments based on distribution of costs of the entire telecom sector that suggest simplicity will minimize total system costs, even though it might lead to seemingly inefficient use of transmission and switching [46, 49, 50]. These arguments are even more persuasive now, when transmission prices have crashed, then in the mid to late-1990s, when those prices were rising [16]. The counterargument, though, is that this trend has been shown by the telecom crash to lead to ruin. If service providers can only sell commodity undifferentiated transport, and most of the intelligence is at the edges of the network, in end-user equipment, carriers will simply not invest enough to build out the necessary networks. And indeed, the cash flow of the telecom service industry is very healthy, and debts have been whittled down. On the other hand, capital investment is extremely depressed, as carriers wait for profitable opportunities.

Thus even if it is not optimal from a global point of view, it might be necessary to introduce complexity in order to be able to construct and operate the telecom infrastructure, especially the residential broadband networks that are so eagerly awaited by government and industry leaders [58]. That might mean allowing carriers to charge differently for movie downloads than for Web surfing. That, in turn, might require a new network architecture. Such a move would not be unprecedented. The key (although seldom mentioned) factor behind the push for new network architectures appears to be the incentive to price discriminate. It is an incentive that has been operating since the beginnings of commerce. Throughout history we observe many practices, such as early postal rates that depended strongly on distance and weight [51], that can only be justified in terms of need to price discriminate. As yet another example, consider the following incident from the early days of the telephone (p. 102 in [44]):

> In Britain in 1889, postal officials reprimanded a Leicester subscriber for using his phone to notify the fire brigade of a nearby conflagration. The fire was not on his premises, and his contract directed him to confine his telephone "to his own business and private affairs." The Leicester Town Council, Chamber of Commerce, and Trade Protection Society all appealed to the postmaster-general, who ruled that the use of the telephone to convey intelligence of fires and riots would be permitted thenceforth.

Table 1. Value of bits: Cost per megabyte of various services.

service	typical monthly bill	revenue per MB
cable	$40	$0.00012
broadband Internet	$50	$0.025
phone	$70	$0.08
dial Internet	$20	$0.33
cell phone	$50	$3.50
SMS		$3000

Such practices are motivated by the wide dispersion in willingness to pay. Different people are able or willing to pay wildly differing amounts in total for all telecom services. Further, individuals, even with the same total willingness to pay, vary substantially in how much they are willing to pay for particular services. As a simple example, Table 1 shows estimates of what U.S. residential users pay per megabyte of traffic from various sources. The methodology used in constructing the table is only approximate (for example, the cable TV rate is computed by assuming average daily viewing time of four hours, with a signal carrying 6 Mb/s, and the SMS rate comes from assuming an average of 33 bytes per message, at 10 cents for each message), but the wide range of prices is striking and persists even if we modify the assumptions underlying the calculations within reasonable bounds.

The basic problem that the telecommunications industry is struggling with is that of moving away from vertically integrated service providers, each with its own technology. The natural evolution is towards a heterogeneous mix of physical access methods, which will be largely invisible to the users, and will be unified by the Internet Protocol. If this scenario plays out, the end-user will have available a simple data pipe (of bandwidth depending on location, willingness to pay, and so on), and services such as voice or TV will be delivered inexpensively over that pipe. This will replace the current mix of different vertically integrated networks designed for different services. The problem for carriers with this scenario is that it is the basic transport service that is likely to be the most expensive. Services (at least the familiar services such as voice) appear likely to cost less and less to deliver (aside from fees to content providers).

If one thinks of services in terms of bits (as much of the industry and even research community do, even though there is plenty of evidence this is misleading), then the great disparity in valuations in the table above suggests keeping different services separate, as SMS is kept separate in wireless communication from voice. Even if one runs a single unified network, those disparate valuations suggest that one should charge according to the nature of the traffic, and not by the byte. But that goes counter to the nature of the current Internet.

As I will show in this paper, price discrimination had been practiced in telecommunications and transportation for a long time. The value of differential pricing has been well understood in economics since the middle of 19th century (although the earliest research in this area has been neglected in history books [23]). But it has been practiced far longer. Table 2 shows some of the tolls charged by the Beverley Beck Navigation in 18th century England. (The full toll schedules were quite long, and can be found in [65], and will

Table 2. Selected 18th century tolls on the Beverley Beck navigation (in pence per ton).

cargo	before 1744	after 1744
sand	2	2
timber, stone, salt	4	6
iron and lead	4	12

be mentioned later.) The “before 1744” column shows the charges according to the 1726 charter, the “after 1744” column those after a revised charter was granted in 1744. These tolls were entirely separate from charges for carriage, which were paid to boat owners. The navigation project did not have any costs that depended on the nature of the cargo. (The project’s costs were primarily the costs of dredging the channel. To the extent that boats being towed through the channel created waves that damaged the banks, or the towpaths got worn, the associated expenses were the same whether the boat carried salt or iron or nothing at all.)

Let us illustrate how this applies in the context of the current controversy over VoIP. The main advantage of VoIP is usually claimed to be greater efficiency in utilization of network resources. Sometimes this is explained as coming from compression of voice signals and better multiplexing of packets than of ordinary voice telephony streams. Yet VoIP is arguably much less efficient in use of basic transmission resources than traditional telephony. Most current VoIP implementations do little if any compression, in order to provide high quality. Moreover, because of the structure of the industry, and the peering arrangements among Internet backbones, most VoIP calls in the U.S. travel over extremely long distances. In contrast, even ordinary long distance voice calls are mostly local, with average distance of about 500 air miles between the two ends [16]. Furthermore, most voice calls are local [51], so the average distance of all voice calls is on the order of 100 miles. In additioin, it was observed in 1998 that it then cost most corporations more to send data over their internal long distance data networks than it would have cost to send it using a modem over the voice network, paying retail rates for the voice calls [46]. Even today, that is still probably true for many enterprises. Analyses of current VoIP technologies for the enterprise environment find few savings, and as a result relatively slow adoption [5]. Thus the efficiency argument for VoIP is questionable at best. This argument was suspect from the very beginnings of VoIP, since basic network costs of traditional voice telephony were very low already in the mid-1990s, and systems for compression of traditional voice telephony were widely available (but were used primarily on links to less-developed countries, and were used on a declining fraction of calls even there).

In the long run VoIP is bound to win because of the new features it makes possible, such as higher quality voice, and integration with other services, as well as the advantages of not having to run a separate network. In the meantime, the main incentive for VoIP comes from the ability to get out of the elaborate maze of cross-subsidies, discriminatory pricing policies, and taxes that are built into the current telecom system. The question is whether the telecom industry can survive in the broadband era without another maze of cross-subsidies, discriminatory pricing policies, and taxes. That the Internet has thus far developed with an open architecture and simple pricing does not mean that it can do so in the future. The Internet has been a small factor in terms of revenues so far, and has benefited tremendously from being able to exploit the infrastructure built primarily for voice services. Currently spending on the Internet in the U.S. is only around 10% of total telecom revenues, as is discussed in Section 8. The question is how the industry can evolve as all the traditional revenue-producing services begin to ride on top of the Internet. To illustrate what the apparent difficulties are, let us consider a simplistic economic model. Suppose that a carrier has two customers, A and B. Suppose further that A has a single phone line, and pays each month $20 for the basic connection (including unlimited local calls), $30 for long distance calls, and $20 for an Internet account (with dial modem access, using the basic phone line). Suppose that B, because of some combination of greater income and greater interest in telecommunications, pays $40 per month for two phone lines, one to be used primarily to access the Internet, $20 for an Internet account, and $70 for long distance calls. Thus the service provider receives $160 per month from A and B (if, as is common, a separate ISP provides Internet connectivity).

Suppose the carrier now offers broadband connectivity. The superior quality makes A willing to spend a total of $80 per month, and B a total of $150 a month. But suppose that they can get the services they want (such as voice) from some other suppliers, on top of their basic broadband pipe, for $10 for A and $20 for B. Then the willingness to spend on that basic connection is $70 per month for A and $130 for B. If the carrier can get that much from each, it can get $200 per month, more than it used to with traditional telephony. That might make it worthwhile to provide the broadband connection. But if the carrier can only offer a basic broadband connection for a uniform price, the most it can get is $140 per month, which might not be sufficient to pay the costs of providing that service. That is the real dilemma for telecom service providers. Can they extract enough money from their customers to pay for broadband, if broadband is just a pipe? Note that the problem can be solved if the carrier is granted the power to price discriminate, and charge customer A $70 and customer B $130.

Giving carriers the power to price discriminate could provide more funding for networks not only from customers, but also from content providers. Suppose there are many residential customers for a carrier, and digital versions of two movies, call them X and Y, each one of 2 GB, are offered by a studio. Suppose that the studio can get $5 for X per household through DVD rentals or movie theater tickets, and $10 for Y. Suppose that we have a secure digital movie distribution system (either through technological solutions or through draconian enforcement of copyrights) so piracy is not a problem, and all customers have the same tastes, and are willing to pay an extra fee (compared to renting a DVD or going to a movie theater) of $3 for X and $5 for Y. The film studio and the carrier, both being profit maximizing entities, will ensure then that the price per movie paid by consumers for home consumption is $8 for X and $15 for Y. If the carrier gets to charge per byte, and charges $1.50 per GB, it will collect $6 per household for downloads of both movies. The studio will get $17 per household. If the carrier can control traffic on the network on a fine scale, it can use differential pricing, charging $3 for X and $5 for Y, for total revenues of $8 per household. In that case the studio gets only what it would from other distribution channels, namely $15. (In practice, of course, the studio would have to get some cut, but it might not be very high. Today, cable TV networks in the U.S. spend only about a quarter of their revenues on content, the rest going into their pockets to provide for network construction and maintenance, overhead costs, and profits.)

As our economy evolves, the incentives to price discriminate are increasing, as fixed costs grow while marginal costs decline. At the same time, the ability to price discriminate is growing. Decreasing privacy along with development of digital rights management tools and the move away from outright sales to licensing provide improved methods for determining how much customers are willing to pay, and to prevent arbitrage, in which those able to buy at low price resell to those the producers insist on charging high prices to. (The prototypical example is the positive passenger identification system, which enables airlines to enforce their contracts, which are for personal service to specific individuals, and are not transferable. See [59] for more detailed discussions.)

Charging by the value of the traffic (or some approximation to it) runs counter to the basic architectural principles of the Internet, principles that were key to its success. The end-to-end principle [67] is the most important of these, and says that functionality should be be concentrated at the edges of the network to the maximal extent possible. In addition there is the open architecture, and lack of discrimination, with all packets treated equally, enabling end users to create new services without involving carriers. This leads to the image of the Internet as the "stupid network" [35], which simply takes packets and delivers them to their destinations. (For further discussion of the effects of an open architecture built on end-to-end principles on innovation in telecommunications, see Section 6.)

What are the prospects of major architectural changes in the Internet? Traditional telecommunications regulatory literature does not offer much help, in spite of its sophistication, with considerations of Ramsey prices and the like, as it was developed for a relatively static technology. This paper presents some historical sketches of the evolution of several network industries in telecommunications and transportation. One can question just how relevant these sketches are, since they concern obsolete technologies. Still, the basic problem is not novel. It is how to charge for a network service, especially when the marginal costs of using it are low. Moreover, at the level of business models, the approaches being proposed now are basically the same as have been used before. Thus it might be interesting to observe how the questions we are facing today were answered in the past.

As was mentioned before, in telecommunications, the trend in general has been towards increasing simplicity in pricing. On the other hand, in transportation we find many instances of increasing sophistication in pricing, and almost a general principle of charging according to the value of the goods being moved (and thus without the end-to-end principle and without privacy). Thus those arguing for a new architecture for the Internet that would limit its openness and ability to innovate do have numerous historical precedents on their side.

Many opponents of increased carrier control over telecommunications are concerned about restrictions on political or personal activities this might entail. And there are certainly many governments that are attempting (in many cases successfully) to restrict what their citizens can do on the Internet. The history of transportation shows pretty clearly, though, that the main impetus for fine-scale control over goods being transported came from economic incentives. Charging tolls for canal transport of iron that were six times higher than those of sand (see Table 2) was a reflection of desire to maximize revenues, not political control. This reinforces the surmise that economics is the main threat to the current Internet architecture.

There is no definitive treatment of the history of pricing in various network industries. Even some basic questions, such as the nature of the "just price" doctrine of medieval scholars, are still being debated. What is indisputable, though, is that price discrimination has been a central concern for a long time. Common law and legislation have attempted to restrain it, but at the same time to allow it to a substantial degree, in order not to lose all benefits from differential pricing. To cite just one example, a British court decision of 1869 (cited on p. 191 of [39]) declared that "At common law, a person holding himself out as a common carrier of goods was not under any obligation to treat all customers equally. ... All that the law required was that he should not charge any more than was reasonable."

The next few sections (2 through 5) outline what happened with lighthouses, canals, turnpikes, and railroads. There has been and continues to be a pervasive tendency in these industries to price according to the value of service, which requires information and control over what was being carried, in complete opposition to the spirit of the end-to-end principle. The general conclusion is that there are extensive historical precedents as well as arguments based on economics for new network architectures that would allow carriers increased control. However, there are also strong arguments for open networks. Then Section 6 discusses the connection between open architectures and innovation, especially in telecommunications. Section 7 is a brief survey of developments in telecommunications pricing. Section 8 is devoted to some projections of future evolution of the telecommunications industry. Final remarks are presented in Section 9. Open networks not only allow for greater innovation, but are more consistent with the likely evolution of telecommunications, towards a variety of technologies providing an interoperable network unified by the Internet Protocol, and with costs concentrated at the edges. They are also far more consistent with the nature of the demand for telecommunications. Hence it appears that there are good prospects for the preservation of an open architecture, although this is not a foregone conclusion.

2 Coase's lighthouse myth and other maritime tales

Ronald Coase's 1974 paper [15], "The lighthouse in economics," has had tremendous impact on economic thought. It claimed to show that lighthouses, which had often been cited as prototypical examples of public goods that only governments can provide, had in the past been provided in England by private enterprise. This suggested to many that the role of government could be shrunk, as many of its functions could be provided by profit-making entities acting in their own interests, hopefully with some gain in economic efficiency. The Coase paper continues to be cited frequently as a breakthrough result. Unfortunately, many conclusions drawn from Coase's paper are unjustified. As an example, a recent commentary [74] claimed that Coase had shown that "[i]nstead of the government-sanctioned 'light dues' charged by Trinity House, developers persuaded ship-owners to sign up in advance for voluntary tolls." This claim from [74] is incorrect, as are many of the conclusions commonly drawn from Coase's paper. In defense of Coase, it has to be said that in his paper he never referred to "voluntary tolls" and did not make the extreme claims some of his followers have put forth. However, Coase's paper uses very ambiguous language to describe the English lighthouse system, and is deeply flawed. Amazingly enough, even though any serious economic historian should have been able to see instantly the faults in the paper, it continued to be accepted uncritically for a quarter of a century. The first debunking appears to have been by Richard Epstein in 1999 [24], and a more thorough one was presented by Daniel Davis in 2002 [18]. (For an earlier, weaker, criticism of the Coase paper, see [73] which has an excellent short summary of the key issues related to public goods.) These contributions are not very well known even today, though.

For an easily accessible history of British lighthouses, see [72], from which much of the information below is taken. What are the basic problems with Coase's paper? It is true that lighthouses were frequently constructed, operated, and owned (with rights of inheritance and sale) by private individuals. However, they were only exceedingly seldom the result of freely negotiated private contracts. They were usually the result of a grant (called a "patent" in those days) from the king, sometimes for a few decades, sometimes in perpetuity. This grant entitled the holder to construct a lighthouse in a particular location and to collect compulsory fees from all ships entering nearby harbors. The fees were set by the terms of the grant, and were often collected by government customs agents. Moreover, lighthouse owners did not just have the right to collect the dues. They had the obligation to provide lighthouse services. We read, for example, of King James I in 1623 reducing in half the compulsory levy for a lighthouse that was poorly maintained [72]. There were instances of grants that did not entail the right to collect compulsory lighthouse duties, but those (as anyone before Coase would have predicted) were generally not successful [72].

Some of the privately owned lighthouses were extremely lucrative. When they were taken over by the government in the 1830s and early 1840s, owners were compensated. The record payment was to the owners of the Skerries Rock lighthouse, who received approximately \$2.2 million. (In comparison, the Louisiana Purchase cost the U.S. \$15 million, and the acquisition of Alaska \$7.2 million.) Still, these private lighthouses were clearly agents of the government. They had the duty imposed by the government of providing services. They also had the power of compelling payment (at least for ships entering British harbors), even from ships that did not rely on them. Shipowners did not have the option of saying that since their ships would only sail in daylight and fair weather, they did not need lighthouses and did not have to pay. The lighthouse arrangement was similar to many that governments used to employ in order to compensate for the lack of information and control technologies. "Tax farming" and even sales of officer positions in armies were common in Europe well into the 19th century. Yet it seems that everybody agrees that these were public goods provided by governments. Thus Coase's lighthouse paper certainly fails to support the thesis that is ascribed to it in places such as [74]. A good overall summary of Coase's paper is in a phrase that Coase used to refer to the works of John Stuart Mill, Pigou, and Paul Samuelson. It makes "statements about lighthouses which are misleading as to the facts, whose meaning, if thought about in a concrete fashion, is quite unclear, and which, to the extent that they imply a policy conclusion, are very likely wrong" [15].

The discussion of Coase's paper serves to point out how misleading myths can survive for a long time, even when there is abundant evidence showing they are false. It also leads to the heart of this section, namely charging. British lighthouse dues were fixed by royal charters. Lighthouse owners could not modify them unilaterally to maximize their profits. Still, there was evolution in charging. What we observe is that as time went on, schedules of fees tended to become more sophisticated. The first recorded grant, from 1261, provided for a fee of two pence for each ship [72]. By the 16th century, we see payment schedules of 6 pence for a two-masted ship, 4 pence for a one-masted ship, and 2 pence for other vessels. In the 17th century, charging according to the cargo-carrying capacity of the ship becomes dominant. By the end of the 19th century, we find the system described by Coase [15], in which ships paid a fee (depending on their cargo-carrying capacity) for each entry into or exit from a harbor up to a certain number, and nothing more for the remainder of the year. (Such two-part tariffs do have significant advantages in collecting payments for services with low or zero marginal cost, as was argued by Coase in another paper [14]. We do encounter them in everyday life, for example in restaurants that offer free refills of coffee or other drinks.)

British lighthouse duties show growth in complexity, but these levies did not require knowledge of the nature of the cargo, if any. Moreover, government acquisition of private lighthouses, authorized by Parliament in 1836, was stimulated by a desire to lower the level of fees and also to make them more uniform. Many of the complaints were about the complexity and the associated non-monetary costs of the old system. (This was a time of the great movement to liberalize trade, reducing tariffs and other impediments. The famous Rhine tolls were abolished in that era as well.)

In general, lighthouse dues appear to have been only a small part of the total cost of shipping. Coase [15] cites figures for 1971-1972 that indicate that revenues of the General Lighthouse Fund were then on the order of two thirds of one percent of the cost of running ships trading with the U.K., and thus a tiny fraction of the value of the goods shipped. Some rough estimates show that this was also true in medieval times.

It is particularly noteworthy that lighthouse charges grew in complexity even though they were low compared to other costs involved in shipping. As was remarked by Coase [15], it is hard to imagine that many decisions whether to make a voyage, or from which harbor to make one, depended on the level of lighthouse fees. It would be nice to investigate this evolution in sophistication of charging schemes, to find out what kinds of arguments were used for and against it. It is likely that it was concern about fairness (and the related issues of shipper complaints and evasion) that dominated, as has been true historically, and is likely to be increasingly prominent in the future [59, 61, 62]. The pricing of goods and services of low marginal cost is often a matter of moral philosophy. It is not uncommon for people with no direct interest in the subject to argue vehemently that flat rate pricing is morally wrong because it forces light users to subsidize heavy ones, say.

British lighthouses provide an interesting example of pricing that was moderately complicated and intrusive. Other countries had other policies. The U.S., for example, has from the beginning had lighthouse service provided by the Coast Guard, paid for out of general federal government funds. A different and very interesting example is that of the Danish Sound Tolls. Their records have been studied extensively, since they are unusually complete and provide an unparalleled view of the economy of Northern Europe. Collected in Helsingor (the Elsinore of Shakespeare's *Hamlet*), the Sound Tolls evolved, primarily in the 1548-1567 period, out of "beaconage," "a minor ship-toll in two classes according to the sizes of the ships" (p. 301 in [13]) for providing navigation beacons. In 1548, a "lightage" levy of 1% of value of cargo was imposed on goods shipped by merchants of some countries, and in 1567 "lastage," a duty based on volume measurement of ships, was introduced. The structure and the level of the Sound Tolls kept changing, and were very complicated, since international treaties meant charges levied on cargo varied depending on the nationality of the cargo owner (not that of the ship carrying the cargo). For more details, see the books [13, 41]. The interesting point is that as the Sound Tolls' bite increased, so did their sophistication. Initially lastage was projected by Danish financial leaders as a fairly simple levy, "based on cargo capacity, with ships in ballast paying half." However, customs officials persuaded the king to modify it, so that "from the very beginning [it was] collected not according to number of lasts, but to a specially elaborated *tariff*, in which the rates were not only adapted according to the units of weight and measure used, but also graduated according to the kind and value of the merchandise" (pp. 299-302 of [13]).

Modern economic concepts and models were not available back in the 16th century, but decision makers often did come up with ingenious schemes. For example, the *ad valorem* levy was on the declared purchase price of the cargo, which produced obvious incentives to falsify documents to show low value. To deal with such abuses, the Danish crown had the right to purchase goods at the declared value [41], diminishing the incentive to cheat too badly.

Compared to British lighthouse duties, the Sound Tolls were much higher, and more intrusive, since they required detailed information about the nature of the cargo, both its value and its ownership. Complaints and abuses were frequent, and led to simplification. First a treaty of 1841 led to relatively uniform *ad valorem* 1% toll, and then in 1857 the Sound Tolls were abolished entirely. The abolition was the result of several countries, including the U.K. and the U.S., paying a lump sum to the Danish government. The motivation was to free international trade of what was perceived as a costly encumbrance. The Select Committee on Sound Dues of the (British) House of Commons in 1856 complained of the level of dues, "but mainly [of] the manner in which they [were] collected."

3 Canals and river navigation projects

During the Ming dynasty in China (14th to 17th centuries) charges for commercial shipping on the Grand Canal were a combination of simple charges based on cargo-carrying capacity of a boat, a charge based on the value of the cargo (initially nominally 1/30 of the market value, with some exceptions), and a few other fees [34]. The *ad valorem* charge was part of the general excise tax system used in China at that time, and in many cases apparently "was omitted, after the tonnage was paid" (p. 176 of [34]). In general, though, the excise tax was very elaborate, and at the end of the Ming dynasty had listings for more than

1,900 articles. There were various irregular exactions by officials, and "[t]hroughout the Ming dynasty few complaints about business taxes were directed to the rate, most them were about abuses and duplicated collections" (p. 184 of [34]). The key point for us is that there was extensive charging according to the value of the cargo.

In England (as well as in many other countries), canals were preceded by river navigation projects. Government was active in two main areas. One was in controlling the exactions of mill and weir owners, who often charged what were regarded as extortionate fees [71, 78]. The other, which developed more slowly, with the most intensive growth starting in the early 17th century [78], was in authorizing navigation improvement projects. These were usually based on permissions given to private individuals, municipalities, or monasteries to dredge rivers, or straighten their courses, or construct locks, in return for the right to levy fees on boats. There appeared to be substantial variation in charging schemes, with a general tendency towards schemes that are more elaborate and correspond more with the value of service. The very first Act of Parliament in this area was for improvements on the river Lea in 1424. A subsequent Act of around 1430 provided for a toll of fourpence for each "laden ship or boat leaving or entering the river" (p. 469 of [12]). Later, on the Thames (which for many centuries was a vital commercial artery for England), tolls for using locks were generally per ton of capacity of boat, usually for round trip, sometimes per passage, and sometimes if a boat returned empty, half the toll was rebated (p. 162 in [71]). A lease from 1638 provided for flat rates for each passage up or down, but with different rates for flat bottom boats and barges (pp. 75-76 in [71]). The nature of the cargo, and even the volume of freight carried, did not play a role. With time, though, we begin to see increased reliance on charging according to amount of goods shipped, usually by weight.

The evolution of tolls is nicely illustrated by the Beverley Beck navigation project, described in [21]. This was operated by a municipal non-profit organization, although the revenues were sometimes used for purposes such as street repairs, and not just for improvement of water transport. The first Act of Parliament, enacted in 1727, had fairly simple tolls, although there was variation even there, with sand charged 2 pence per ton, and salt, iron, lead, timber, and stone 4 pence per ton [65]. (The actual list was considerably longer, and included items such as 4 pence for each 32 firkins of butter. All references to pence in this paper are to the old British pence, with 240 of them to the pound.) This was insufficient to cover the costs, and in 1744 (according to [65], and in 1745 according to [21]) the navigation corporation petitioned Parliament, asking for a more appropriate toll schedule. The basic point they made was that "[p]art of the trouble lay in the tolls not being proportionate to the value of the goods transported" (p. 9 of [21]). Parliament responded by granting a new charter, with a more elaborate and generally higher toll structure. (But it appears from the remarks in [65] that a restriction was imposed, forbidding the use of these toll revenues for purposes other than improvements of navigation.) Charges for sand remained at 2 pence per ton, those of timber, stone, and salt were raised from 4 to 6 pence per ton, and those for iron and lead raised from 4 to 12 pence per ton, as shown in Table 2 [65]. The change in tolls, along with other changes in policy, and possibly a generally growing level of economic activity, did bring a measure of success to the Beverley Beck project. The interesting point here is that this was a non-profit enterprise that operated right on the verge of sustainability, and a rebalancing of tolls appeared to make a measurably positive impact.

Canals were the next step up from river navigation projects in complexity, cost, and efficiency. An interesting example is presented by the Dutch *trekvaarten* system of canals and canal boats constructed for passenger transportation in the middle of the 17th century [19]. It provided the Netherlands with a communication system that for over a century was superior to that of any other country. Various pieces of the system were built by agreement between pairs of cities. Hence, as has traditionally been common with government systems, there was simple and inflexible pricing, with two classes of service, and fees that did not vary much over a century and a half. With time, though, incentives to price discriminate began to make their mark, and provisions were made for cut-rate or even free travel by the poor. Overall, though, there was relatively little price discrimination, and pricing was rigidly controlled by city governments. The general rigidity of the *trekvaarten* system imposed by government construction and control did lead to some missed opportunities to make this once-novel system more competitive with emerging alternatives, see [19].

The Dutch canals were built in a very favorable terrain of a flat country, with easy to handle soils and plenty of water. A far more challenging project was the French Canal du Midi, also called the Canal du Languedoc, constructed at the end of the 17th century (during the reign of Louis XIV) to provide an inland link within France between the Atlantic ocean and the Mediterranean. It was a stunning technological achievement. It was also a financial dud for its government and private investors. Still, tolls on this canal were from the very beginning dependent on the nature of the cargo, with an elaborate schedule of fees (pp. 193-197 of [42]).

Although the technology of the Canal du Midi was widely known and admired, its poor financial results appear to have deterred attempts to imitate it. The modern canal era can be said to start with the Duke of Bridgewater's Canal in England. Originally it was just a means of connecting the Duke's colliery to Manchester. The parliamentary charter (which enabled him to take over private property, with appropriate compensation) obliged the Duke to carry cargo to Manchester at a maximum charge of 30 pence a ton, and to sell his own coal in Manchester for no more than 80 pence a ton, about half the price that had prevailed before [38, 65]. Parliament was determined to obtain substantial benefits for the public from the grant of government powers to the Duke.

The initial canal designed and constructed by Brindley for the Duke of Bridgewater was soon afterwards extended to a canal providing a general freight connection between Liverpool and Manchester. This was then followed by other canals. Interestingly enough, in the deliberations leading to the grants of charters for some of these projects, owners of river navigation projects that were likely to be adversely affected by the competition sometimes argued that even if a canal charter were to be granted, it should allow only for tolls based on weight of cargo, independent of the nature of the cargo (p. 101 of part 2 of [10] and pp. 194-200 of [64]):

> The owners and trustees of the old navigations beg leave to submit, "that the tonnage, collected by the company of proprietors, ought to be equal, through the whole canal, for every species of goods; with some particular exceptions."

(Note that even these petitioners could not deny completely the logic of differential pricing, and felt compelled to allow for "some particular exceptions." At an even more basic level, charging by the tons of cargo is already a nod in the direction of price discrimination, since costs of operating a canal depend only on the damage done by a boat, and that has little relation to the cargo that is carried.) The power of price discrimination was understood very well in those days, and was greatly feared. There was a frequently expressed and strong preference for simple rates. As an example, consider the following passage from the Preface to [64]:

> When the carriages which pass over a highway or a bridge, and the lighters and barges which are used upon a navigable canal, pay toll in proportion to their weight or their tonnage, they pay for the maintaining those public works in proportion to the wear and tear which they occasion. A more equitable way of maintaining such works cannot be found; for the tax or toll, though advanced by the carrier, is finally paid by the consumer, to whom it is charged in the price of his goods.

But the incentives to price discriminate were powerful enough to overcome such moral concerns.

The great financial success of the Duke of Bridgewater's Canal (which was reputed to earn profits of well over 100% on invested capital in the early 19th century) led to widespread attempts to emulate it. In the early 1790s, there was a canal mania, with a burst of construction that was never to be replicated in Britain. (The U.S. had its canal mania some decades later, following on the great success of the Erie Canal.) The charters of those canals show a general trend towards greater price discrimination. (There is an excellent summary source on canal charters in the compilation [64]. It is hard to do careful quantitative studies with that data, though, until one obtains more information about expected traffic on the various canals and the political factors that were involved in the parliamentary decisions.) As described by one historian, "whereas the Trent & Mersey in 1766 had been granted tolls of [1.5 pence per ton per mile] on everything, the Grand Junction in 1793 was given [1 pence] on merchandise, [0.75 pence] on coal, [0.5 pence] on building material, and [0.25 pence] on lime and limestone" (p. 78 of [32]). There was also almost a universal requirement in charters that forced canals to allow for free carriage of manure for adjacent fields as well as of stone for road repairs. Unfortunately there do not appear to be any studies of the reasons for the wide variation in toll schedules. Were they selected with some careful thought on their economic impact, or just in response to political pressure from local interests?

Similar toll schedules depending on cargo were also common in the United States. As an example, when parts of the still incomplete Erie Canal were opened in 1820, there was a long list of tolls, concluding with "All articles not enumerated, one cent, per ton, per mile" (Chapter 2 of [76]). The enumerated articles (among those that were measured by the ton) were charged tolls ranging from salt and gypsum at 0.5 cents per ton per mile, to 1 cent for flour, to 2 cents for merchandise, and nothing for fuel to be used in the manufacture of salt (so that it was necessary not only to know the nature of the cargo, but its ultimate use).

It is worth noting that canal tolls were a very substantial part of the cost of canal transport. There do not appear to be any systematic studies on this subject, but there are various snippets of information that suggest tolls often were more than half the total cost. (For example, p. 128 of [78] mentions a certain canal, where transport of a chaldron of coal was expected to cost 30 pence for tolls and 18 pence in fees to carriers for use of the barge.) Thus, unlike for the telecommunications case to be discussed in Section 8, there were high costs in the core of the network.

Today, canal and maritime tolls still vary, and often depend on nature of cargo. The Erie Canal is open again, and is used almost exclusively for recreational purposes. The tolls for private boats depend just on the length of the boat. Fee schedules for commercial vessels are complicated, including flat annual fees. On the Panama Canal, tolls depend on the tonnage measurements using that canal's own rules, with charges higher when carrying passengers or cargo, but not depending on the nature of the cargo. On the St. Lawrence Seaway, tolls include charges depending on tonnage measurements, lock fees, as well as levies varying with the nature of the cargo. (For example, in 2002, Welland Canal charges varied from Canadian $0.6072 per ton of coal or containerized cargo, to $0.6956 for steel slab, and $0.9717 for general cargo. Curiously enough, on the Montreal/Lake Ontario section of the Seaway, charges were lowest for coal, at $0.541 per ton, considerably higher for containerized cargo, at $0.9164 per ton, and over four times as high for general cargo, at $2.2081 per ton.)

Canals in England were traditionally strongly restricted to offering superior water transportation facilities to carriers, and generally could not act as carriers themselves. (This prohibition was only eliminated in 1845, in order to strengthen canal operators in their competition with railways. However, as is noted in [22], there were instances of canals experimenting with provision of direct carriage before that time.) Thus this was an early example of the kind of structural separation that is occasionally being proposed for telecommunications, with a basic network operator and other operators providing services on top of that operator's facilities. However, canals did search for other ways than those specified by their charters to increase their profits, and to price discriminate more effectively than allowed by their charters' toll structures. Since actual tolls were often below the maxima specified in the charters (as the canals maximized their revenues), there was wide scope for varying the relative charges on different types of goods. (Unfortunately there do not appear to be any studies of the extent to which actual charges varied from the statutory ones.) Although tolls were supposed to be uniform and proportional to mileage, rebates offered a way around such rules. There were many other practices by canals that were regarded as abusive. In particular, canals would often gain control of all warehouses in their vicinity. Complaints about canal pricing, both as to the level of fees and to the extent of discrimination, were among the major reasons for the interest in development of railways [36]. Many of the complaints were not about canal operators, but about canal boat operators, who were generally not regulated (except for sporadic price limitation moves), and engaged in their own forms of price discrimination and other widely disliked pricing practices.

While canal operators were trying to squeeze carriers (who were trying to squeeze merchants, in ways similar to those described below for turnpikes), carriers often attempted to evade tolls. They bribed toll-collectors, misrepresented what the cargo was, or how much there was of it, and in some cases even hid cargo with high toll charges under commodities such as sand for which the fees were low. The countermeasures, just as they are today, and would likely be in the future with electronic communications, were based on both technology and law. Measurements were taken (in many cases there were books available to canal operators, listing canal boats, and the weight of cargo aboard as a function of how deeply in the water they lay), and there were punitive penalties for evasion. For fuller discussion of this phenomenon in England and the United States, see, for example, [29, 31, 32].

4 Turnpikes and modern road transport

British turnpikes were a controversial response to a serious problem. Traditionally, the King's Highway was open to all. The problem was how to keep it in good condition. As commerce grew, the need to maintain roads became acute. At first, in Elizabethan times, laws were enacted compelling all able-bodied commoner males to devote several days a year to labor on the highways. (See [1, 63, 75] for references for the background information as well as other items below that are not attributed otherwise.) The inequitable distribution of the burden this imposed and the lack of effective control mechanisms by the central government led to many complaints. As a result, in 1663, the first turnpike was authorized. It was very controversial, since for the first time it required payment for traversing the King's Highway. Apparently largely for that reason, it took until 1695 before the next turnpike was set up [2].

In the early 18th century, the turnpike movement took off in earnest. Although there were frequent protests (sometimes violent, as in the burning of the toll gates around Bristol in 1727 and 1735), by mid-1830s there were over 20,000 miles of turnpikes in England. As stated on p. 202 of [63],

> The schedule of tolls chargeable by each trust was laid down in its Act. These varied considerably from trust to trust, ... The schedule itself was designed to cover all those categories of traffic which were considered to be a charge on road repair, differentiating to a certain extent on grounds of size and ability to pay. Each schedule was qualified by a list of exemptions and qualifications ...

Tolls were usually doubled on Sundays for ordinary commercial traffic, but were eliminated for travel to or from church. They also "were never levied on foot passengers, and were thus unfelt by the labouring poor" (p. 124 of [75]). There were also options in many cases for a flat fee for annual access. Still, there were countless controversies about the toll, "the collection of which led to endless evasions, inequalities and favouritisms of all kinds, arbitrary exactions, and systematic petty embezzlements" (p. 136 of [75]). As with canals, there do not appear to be any studies on how the widely varying toll schedules were determined.

Road transport presents an interesting contrast with canals. Road tolls formed a much smaller fraction of road carriers' costs than they did for canal carriers. It appears that in early 19th century Britain, tolls were 10-15% of carrier costs (Chapter 6 of [27], especially Table 14 on p. 129). On the other hand, feed for horses was more than half of the costs. Thus variable costs were very high, which lessened incentives to price discriminate. Also, because the wagon, the unit of transport, was not all that expensive, shippers could avoid the most extreme cases of differential pricing by operating their own transport systems. Yet price discrimination was rife. Chapter 7 of [27] makes for fascinating reading on this subject. As it notes, the most important factor was "the principle of charging what the traffic would bear." There were variations by type of goods, and of course by locality (reflecting competitiveness of different markets), but "the main distinction was between gents' and trade price," and "gents' price could be anything from a seventh to a half above trade price" (p. 153 in [27]). Some of this differential reflected different costs, and often it was the result of explicit collusion. Still, this differential existed even in competitive situations. This provides yet another example of the phenomenon, going counter to the prevailing doctrines in economics, law, and regulation that price discrimination is not necessarily a sign of monopoly, but of vigorous competition [59].

So far I have been producing examples of the extensive practice of differential pricing on turnpikes and other transport systems. But what did it accomplish? Perhaps it was just a way to transfer money from users to owners, or else it might have been the result of some mistaken dogma. In most cases we have little solid evidence to decide. But there are a few examples that demonstrate the utility of this practice. For river navigation, the Beverley Beck Navigation, cited before, showed what appears to have been a beneficial impact from a more discriminatory toll structure. For turnpikes, we have some very interesting recent studies of Dan Bogart [7, 8]. They show that introduction of turnpikes did lead to a substantial increase in spending on roads. (That is, the turnpike trusts, the non-profit entities improving and maintaing the roads, and collecting the tolls, spent considerably more on the roads than the parishes did on their own, in response to their legal obligation to maintain the King's Highway.) More interestingly, the study [8] demonstrates that "land carriage rates fell by approximately 11-16% after turnpike trusts were adopted." Thus even though the free highway was replaced by a toll road with high charges imposed on carriers, the increased efficiency of transport on the turnpike led to end users paying less than before. Thus one can safely conclude that turnpikes were a positive contribution to society.

The finances of the current road transport systems are hard to disentangle. There are a variety of user fees (registration, fuel taxes) as well as general tax revenues used. It is hard to tell just how much price discrimination is being practiced, but it is extensive (for example, in different charges for freight, as well as in higher profit rates on expensive cars). There are two important factors to bear in mind. One is that most of the costs are born by the end users directly (through purchases of cars, paying for insurance, gas, etc.). The other one is that road tolls are coming back as a result of growing congestion and improved technology. Unlike telecommunications, where technology is increasing capacity of fiber, coax, and radio transmissions, building new roads is increasingly difficult, and making existing ones carry more traffic can only be done to a limited extent. At the same time, electronic means for monitoring traffic and collecting tolls are improving, and we see central business districts in Norway, Singapore, and (since early 2003) London imposing tolls. Most of these systems do raise privacy issues, too, since they are centralized ones with information about users, or at least cars. Still, there is a strong tendency to introduce ever more detailed monitoring of traffic, often with the explicit goal of charging users according to their level of activity (whether by governments or by insurance companies).

5 Railroads

Railroads were the dominant industry of the 19th century. Their similarities and contrasts with the Internet and the resulting implications for the economy as a whole will be explored in [60–62]. Particularly striking are the results about privacy and price discrimination, summarized in the extended abstract [59]. In this section I present just some brief remarks on this topic.

Early railroad charters, in both England and the U.S., were modeled after canal and turnpike charters, and almost uniformly envisaged that railroad companies would not be carriers themselves. Instead, they were expected to offer their facilities for use by carriers that would carry goods and passengers in their own wagons over the rails. Still, these charters specified tolls that varied greatly depending on the nature of the cargo. (Since these were tolls for use of the rails, handling costs were not an issue, as those were covered by carrier charges. Any costs to the railway, such as wear and tear on the rails, were due to the weight of the cargo, independent of what it was.) For example, the very first parliamentary act for a railroad was enacted in 1801. (Previous railways had been on private property, but in this case, as in subsequent ones, promoters were asking for the right of eminent domain to acquire the necessary land.) Between the endpoints of the railway, "chalk, lime and other manures were charged at the rate of three-pence per ton per mile; coals, corn, potatoes, iron and other metals, fourpence; and all goods not specified, sixpence" (p. 45 of [12]). Thus there was no end-to-end principle, no open architecture, and no privacy for the goods that are carried.

An interesting observation is that, just as today, the government was trying to leave as much choice of technology as possible to the market (p. 54 of [12]):

> Parliament wisely refrained from binding the first railway projectors to adopt any specified form of rail. Whether a plank of wood or an iron plate should be used; whether the rail should be laid on stone or on wooden sleepers, should be flanged or smooth, should be flush with the ground, or sunk, or project above the ground, whether the wheels should be cogged or toothed, fitting into the rail as they revolved, to prevent skidding, or should offer a plain surface, guided by the grooved rail:–these were questions with which Parliament did not meddle. Each of these plans, however, had it advocates, and was in turn adopted.

On the other hand, pricing, and especially the extent of price discrimination, were of intense interest to Parliament, and there were attempts to put in stringent limits. That was pretty effective with canals and turnpikes, but not with railroads.

Although some railroads did operate with other companies' equipment on their rails for decades (and modern ones do so extensively), there was a relatively quick shift in the 1830s and 1840s towards railroads being exclusive carriers. There were technical reasons promoting such a shift (safety was jeopardized with multiple operators and primitive technology), but there is evidence that desire for greater control over pricing by railroads was also a major consideration [61]. Once railroads became carriers, they could engage in much more extensive price discrimination than allowed by the toll structure in their charters. And, propelled by the economics of their industry, with high fixed costs, railroads did engage in massive price discrimination, including personal discrimination. The result was massive political movements leading to government regulation [59, 62].

The full story of pricing policies of 19th century railroads is too vast to tell here. I will illustrate it with just one example, that of the "small freight wars" of 1840-1872 in Britain. (A much more detailed description is available in Chapter 5 of [39].) Railroads had high rates for small packages, and low rates for large ones. This opened up a very profitable business for independent parcel-handlers. Purely for purposes of illustration, suppose that there were only two types of packages, of 50 pounds and 1,000 pounds, and a railroad had decided that the profit-maximizing price schedule was to charge $1 for a 50 pound package, and $10 for a 1,000 pound one. An outside agent could ruin this practice by practicing arbitrage, offering to convey 50 pound packages for $0.75 each, and accomplishing this by assembling them into 1,000 pound ones, which it would then pay the railroad $10 to convey (or $0.50 per 50 pound package). That was basically what was happening in Britain in the 19th century. Railroads set out to fight this practice, by refusing to accept such combined packages from independent parcel-handlers, or by charging these shippers punitive rates. The parcel-handlers kept going to courts, which continued ruling in their favor and against the railroads. Still, railroads kept interfering with these carriers by making trivial modifications to their tariffs, just enough to be able to claim they were not doing what had been ruled illegal in the last lawsuit they had lost. (Those familiar with the UNE-P facilities sharing fights over the last few years in telecommunications all over the world may recognize some similarities.)

The point of the example above is that railroads could not resist the temptation to price discriminate even when it was plainly illegal to do so. Moreover, to do so, they had to have knowledge of the nature of the cargo they were carrying.

Eventually, railroad price discrimination led to a revolt, and government curbs on railroad pricing practices. The main complaint was usually less about the level of prices (which were typically far below the maximal levels envisaged in the charters), and more about inequities of differential pricing [59, 62].

Government regulation, imposed at the end of the 19th century, did lead to stability for the railroad industry and prices that the public could be persuaded were largely fair. (It did not eliminate differential pricing for goods, though. The incentive for price discrimination was too strong, and charges continued to depend on the cargo.) However, regulation did strangle innovation in the industry, and resulted in gross inefficiencies. With time, the arguments that the costs of regulation were too high gained ground. In the U.S., railroads were deregulated by the 1980 Staggers Act. As a result, between 1984 and 2001, "inflation-adjusted rail rates fell 45%" [66]. However, there are still complaints about both service quality and the degree of price discrimination. It is estimated "that captive shippers commonly pay rates 20% higher than shippers with competitive alternatives" [66]. The federal Surface Transportation Board can intervene in extreme cases of gouging, but the general perception is that competition from alternative modes of transportation is sufficient in most cases to provide a workable transportation system. It is a system, though, where prices depend on the nature of the cargo as well as local competitive conditions.

6 Open systems and innovation

The power to price discriminate, especially for a monopolist, is like the power of taxation, something that can be used to destroy. There are many governments that are interested in controlling Internet traffic for political or other reasons, and are interfering (with various degrees of success) with the end-to-end principle. However, in most democratic societies, the pressure to change the architecture of the Internet is coming primarily from economic concerns, trying to extract more revenues from users. This does not necessarily threaten political liberty, but it does impede innovation. If some new protocol or service is invented, gains from its use could be appropriated by the carriers if they could impose special charges for it.

The power of price discrimination was well understood in ancient times, even if the economic concept was not defined. As the many historical vignettes presented before show, differential pricing was frequently allowed, but only to a controlled degree. The main concern in the early days was about general fairness and about service providers leveraging their control of a key facility into control over other businesses. Personal discrimination was particularly hated, and preference was given to general rules applying to broad classes (such as student or senior citizen discounts today). Very often bounds on charges were imposed to limit price discrimination.

In particular, the standard economic argument for price discrimination says that personal discrimination (charging two otherwise identical people different prices for the same good or service, if one values it more highly than the other) can also provide substantial value. But that kind of discrimination has traditionally been discouraged. Discrimination on the basis of membership in wide classes (students or the elderly in modern societies, for example) was often allowed, but not personal discrimination. On canals and railroads, officially sanctioned discrimination in freight was based on officially prescribed categories of goods. But sellers have often been tempted to tread in the dangerously sensitive area of personal discrimination.

In many states in the U.S., hotels still post nominal room rates. This custom comes from old historical precedents of innkeeper regulations (which were often used as guides for canal or turnpike rules). But the effectiveness of such approaches is limited, since the nominal rates can be set very high, at levels that are practically never achieved. There is also no assurance that equal rates will be charged to various hotel guests. (Increasingly the rates that are charged vary wildly, as hotels attempt to use airline-style "yield-management" techniques.)

Openness, non-discrimination, and the end-to-end principle have contributed greatly to the success of the Internet, by allowing innovation to flourish. Service providers have traditionally been very poor in introducing services that mattered and even in forecasting where their profits would come from. Sometimes this was because of ignorance, as in the failure of WAP and success of SMS, both of which came as great surprises to the wireless industry, even though this should have been the easiest thing to predict [52]. Sometimes it was because the industry tried to control usage excessively. For example, services such as Minitel have turned out to be disappointments for their proponents largely because of the built-in limitations. We can also recall the attempts by the local telephone monopolies in the mid- to late-1990s to impose special fees on Internet access calls. Various studies were trotted out about the harm that long Internet calls were causing to the network. In retrospect, though, Internet access was a key source of the increased revenues and profits at the local telcos in the late 1990s. Since the main value of the phone was its accessibility at any time, long Internet calls led to installation of second lines that were highly profitable for service providers. (The average length of time that a phone line was in use remained remarkably constant during that period [46].)

Much of the progress in telecommunications over the last couple of decades was due to innovations by users. The "killer apps" on the Internet, email, Web, browser, search engines, and Napster, were all invented by end users, not by carriers. (Even email was specifically not designed into the ARPANET, the progenitor of the Internet, and its dominance came as a surprise [52].) Today, in the wireless arena, the most vigorous growth and innovation is coming in the license-free area, unencumbered by high costs and inflexibility.

Yet the openness of the Internet is also perceived as a major cause of the telecom slump. The end-to-end principle and the open architecture are under assault for many reasons [6, 11], but one of the major ones is that they are widely seen not to allow for viable business models. Email, Web, browser, search engines, and Napster are all great, but appear not to provide any direct revenues for carriers. In contrast, the Minitel design was for a content delivery network, with email specifically not designed in. To the extent that Minitel succeeded, it did so largely because of chat rooms, which were an accidental feature designed for other purposes. Still, Minitel continues to be profitable for France Telecom to this day (if one ignores the huge investment the French government made in the development of the technology). Hence from the standpoint of the service providers it might appear attractive, in spite of its limitations. As yet another example, there are major battles over peer-to-peer music sharing in the wireline Internet, with the music industry generally fighting the ISPs (even if users are the main targets of their assaults). On the other hand, in the wireless area, carriers and music companies collaborate in a mutually profitable business of selling ring tones to users. The architecture of cell phones allows collection of fees from users, and content providers and carriers each get a negotiated slice.

Moreover, it is not just service providers who might like to change the architecture and the business model of the Internet. The "stupid network" is only stupid in the core, and imposes huge burdens on end users [47]. Many of those users might be willing to sacrifice some of the openness and flexibility in order to be relieved of the frustrating chore of being their own network administrators. It is rather ironic that many of the defenders of the open Internet castigate Microsoft for allowing email attachments to be executed. But that was a feature designed to make the PC more open.

Introduction of artificial restrictions on the Internet would be consistent with other trends in the modern economy. In addition to legal measures (such as DMCA), the U.S. government is forcing major architectural changes on the whole IT industry through the requirement for the "digital broadcast flag." The computer industry is contributing to these trends with its development of DRM (digital rights management) and "trusted computing" technologies. The scientific and engineering developments that gave us the openness of the PC and Internet platforms are also enabling changes to these platforms that would restrict what users can do with them.

It is worth noting that should a substantial degree of price discrimination be necessary, some remedies that have been proposed for the problems of the telecom industry would not be sufficient. In particular, structural separation (splitting the local access providers into two parts, one that would be a monopoly provider of local connectivity, and another one that would compete on an equal footing with others to provide services) would likely not be effective. The problem is that it is the basic connectivity piece that is expensive to provide, whereas costs of services are lower and are decreasing much more rapidly. Hence it would likely be necessary to allow the monopoly access provider to price discriminate, and that is hard to do effectively without control over traffic. (Some degree of differential pricing could be introduced without looking at transmissions. That is done today in the U.S. in voice telephony, where basic voice circuits for business use usually cost about twice as much as for residential use. This might not be sufficient, though.)

The general conclusion is that the open architecture of the Internet is a major asset in promoting innovation, but it is not guaranteed to survive just for that reason. However, there are other factors that do argue in its favor.

7 Trends in telecom pricing

The general trend in communications has been towards simpler pricing and decreasing price discrimination. This is described in detail in [51, 53]. There was one notable counterexample, though. The telephone started out with flat rates almost everywhere. The phone companies (private as well as government ones) then fought a worldwide battle, spanning several decades, to switch to metered billing. They succeeded almost everywhere, as is detailed in [51, 53]. They were supported by a remarkable consensus of experts. And indeed, the case for metering phone calls in those days was overwhelming, since there was a high marginal cost associated to each call, as action by an operator was required. The major exception to the switch to metered rates was the United States, where, aside from a few places such as Chicago and New York City, flat rates were preserved for residential local calling. This appears to have been the result of the competition between the Bell System and the independent phone companies. The need to cater to customer preferences meant that expert opinion did not prevail, and metered rates were not forced on everyone.

Although flat rates were regarded as damaging, they did not harm the U.S. telephone industry in the long run, as a comparison with other countries shows [51, 53]. U.S. phone industry revenues have traditionally been higher, as fractions of GDP, than those of most other countries, and the industry was dynamic and profitable. Moreover, flat rates for local calling played a key role in the rise of the Internet, by promoting much faster spread of this technology in the U.S. than in other countries. (This, as well as the FCC decisions about keeping Internet calls free from access charges, should surely be added to the list of "the 10 key choices that were critical to the Net's success," that were compiled by Scott Bradner [28].)

Today, as was already noted in the Introduction, we are seeing the spread of flat rates to long distance telephony and even wireless. Yet although telephony is evolving towards simpler pricing, it did start out with a high degree of price discrimination and elaborate pricing. (That was also true of other systems. For example, postal services started out with distance-sensitive tariffs. Later, after switching to what are now known as "postal rates," independent of distance, they still were introducing services motivated by the incentives to price discriminate, such as postcards. Moreover, although there is a version of the end-to-end principle and open architecture in postal systems, with first class mail generally protected from intrusion by postal employees, book rates involve potential inspections. There are also stringent restrictions on competition, and in the U.S. at least, post office boxes, although owned by residents, can only be used for mail.) As is detailed in [51, 53], the earliest phone rates were twice as high for business as for residential users. (This disparity in charges for basic monthly fees persists in the U.S. to this day.) Later, high long distance rates were used to subsidize basic telephone service and local calling. Evening and weekend discounts were introduced as well (although they are now disappearing.) There were constant attempts to limit what customers could do, as in the Carterphone case in the 1960s where the Bell System attempted to control what could be interfaced with the the phone network, and even in attempts to prevent customers from placing covers on their telephone directories. Hence it is possible to reconcile the view that pricing tends to get simpler and price discrimination decreases with advocacy of complicated pricing and extensive price discrimination for broadband access today. The argument then is that such measures are necessary to develop a new technology, even if eventually they might need to be phased out.

Interestingly enough, even though the wireless industry is congratulating itself from avoiding the open architecture of the Internet, it has been remarkably poor at price discriminating. It has done some (and in particular has managed to charge for each handset). But it has failed to exploit other opportunities. It has fallen for the mirage of mobile Internet access, and has neglected the opportunities in providing differentiated voice services as well as toll-free wireless calling [52, 54, 58]. Such services provide promising opportunities for drawing more revenues from business users that are not being exploited.

8 Telecommunications today and tomorrow

For a discussion of the current state of the telecom industry (with references and statistics), see [57, 58]. Here I just reiterate a few key points, with some additional recent data. Total telecommunications service revenues in the U.S. (and all statistics in this section will be for U.S. alone) is around $300 billion to $350 billion per year. Most of that is voice, with wireless accounting for around $80 billion. Although Internet backbone traffic volumes are much higher (by a factor of more than two at the end of 2003) than long distance voice volumes, Internet revenues are only about $35 billion, with about $15 billion coming from dedicated access, and $10 billion each from dial access and residential broadband access. (To be fair, it should be said that private line and Frame Relay services, which provide intra-enterprise connectivity, bring in revenues of about $30 billion per year to the carriers. Those services are used primarily to carry IP traffic, so they are really part of the Internet, and serve to boost the Internet revenue figure to about $65 billion per year.)

Especially important is the migration of costs on the Internet to the edges. Of the $35 billion in annual Internet revenues, even the $15 billion for dedicated access would shrink to $2 billion if all the traffic coming in were aggregated into large pipes [57, 58]. (See also [45] for costs of broadband access, and how little is for the basic network infrastructure.) The core of the Internet, although of huge capacity, is not expensive to run. Technology has outrun demand, and the entire U.S. Internet backbone traffic could in principle be carried on a single fiber strand [57]. Moreover, prices are still dropping [37]. In addition to the illustrations in [57, 58], let us note that the transatlantic cable constructed a few years ago by 360networks for $850 million was recently bought by an investor for $18 million [4]. It costs about $10 million per year to run, and at time of sale had lit capacity of 192 Gb/s. (With more equipment its capacity can be raised to several terabits per second.) In comparison, in early 2003, total transatlantic Internet traffic averaged only 70 Gb/s (in the U.S. to Europe direction, and 42 Gb/s in the reverse one [70], while the total lit transatlantic capacity was about 2 terabits per second). Hence, given the distribution of demand as a function of time of day and day of week, in principle the entire Internet traffic could have been carried on that single cable, even without lighting up additional capacity on it.

The sale price of the 360networks cable is not an anomaly, as many other distressed carriers' assets are being sold for pennies on the dollar [33]. As a result, fiber on the main long distance routes is essentially free. The costs of lighting that fiber are also relatively moderate, as the discussion of Cogent in [58] shows. Thus the costs of long haul transport are basically negligible compared to total telecom spending, and are likely to remain so for the foreseeable future. They are so low that the "vulture investors" purchasing fiber assets may not realize much value, as the major carriers may in effect give away long distance transport to their customers as a way to hang onto the more lucrative services. Comments that one hears from industry leaders, such as that the "competitive advantage is no longer asset base but the sales and marketing team you've got" [4] reflect this new reality.

The fiber glut is a major contributor to this reduction of the core of the network to a low-cost commodity. However, as is discussed in [57, 58], it is far from being the only reason. Technology had been reducing costs in the core far faster than at the edges even in the pre-Internet days. Even if one had to build a totally new fiber network from scratch, it would not be very expensive. Hence, aside from the incentive to price discriminate, the logical and economically efficient outcome is to run core networks as commodity providers of a uniformly high quality service. Given the degree of competition on major long distance routes and the lack of a player that might have a chance to monopolize fiber supplies, it appears overwhelmingly likely that core transport will continue to evolve towards a commodity. It will likely be profitable eventually for one or two players, after some consolidation, but it is unlikely to be a very large business.

On the other hand, historical precedents strongly suggest that total telecommunications spending should resume growing again, even when measured as a fraction of the economy [51]. Most of that spending is likely to continue to be at the edges of the network. It may also increasingly be in forms that do not produce carrier revenues, as we move to customer-owned networks. (Signs of that are the fiber strands or wavelengths that large enterprises are increasingly purchasing to reach local exchange points, as well as the WiFi and other home networking setups that residential users are buying.) There may be more heterogeneity even in local access, with DSL, cable, and broadband all available to most users.

What we appear to be moving towards is a heterogeneous mixture of networks, unified through the Internet Protocol. Voice will be just one of many services delivered through a broadband link. The resulting system will likely resemble what Ted Stout calls the multimodal transportation system, with many technologies and specialized service providers available, and customers selecting the best one for their needs, often through intermediaries. (And indeed, we are beginning to see the emergence of such intermediaries in telecom [20].) In such an environment, there will be a variety of players, and there will be price discrimination, but not through a single giant monolithic carrier, but through many competing enterprises.

9 Conclusions

The historical precedents presented here, together with basic economic arguments, help to at least partially explain the puzzling behavior of the networking industry, as well as of the networking research community. They have devoted inordinate efforts to technologies such as ATM and QoS, even though there was abundant evidence these were not going to succeed. One can go further and say that essentially all the major networking initiatives of the last decade, such as ATM, QoS, RSVP, multicasting, congestion pricing, active networks, and 3G, have turned out to be duds. Furthermore, they all failed not because the technical solutions that were developed were inadequate, but because they were not what users wanted. The misguided development of these technologies took place because researchers and developers refused to take a realistic look at how networks were used, and how they were likely to evolve. This behavior, though, appears to have been motivated largely by the message they kept hearing constantly from business people that differentiated services were a must. The basic motive for this message appears to have come from the incentive to price discriminate. The historical evidence shows how important a factor that has been in the past, especially in transportation, and so this push is understandable. Going forward, the incentives and the means to price discriminate will be increasing. This will lead to continued and even intensifying threats to the architecture of the Internet, especially the end-to-end principle, and to current business models.

Does this mean that the current architecture of the Internet is lost? Not necessarily. There are several countervailing factors. First of all, there are general public policy concerns. The end-to-end principle, and the general open architecture of the Internet, have proven superb in stimulating innovation and economic growth. And even in earlier times, the destructive powers of untrammeled price discrimination were well understood, and usually strictly limited. (Of course, such limits were often transgressed, most egregiously so by 19th century railroads. Moreover, with the extra flexibility that modern technology provides, there will be ever more ingenious ways to break through barriers that governments might impose.) Typically, stringent limits were prescribed on tolls, dependent on carefully chosen categories. Thus one could make a good case for government intervention to limit carrier practices (as it already does with the traditional voice network). However, based on observations of recent behavior, it appears that governments are much more likely to listen to appeals for closed architectures as short-term aids to industry, than to the promise of greater payoff in the future.

A more persuasive argument for government action might be that closed architectures have all too often been used to produce inefficiency or high profits. There is a growing body of evidence that privatization and liberalization of regulations promote investment, efficiency, and innovation (e.g., consider [17, 25, 77] and the references there). However, that is not necessarily a complete answer either, since competitive markets can be expected to produce intensified price discrimination [59], as happened with airlines and railroads in the U.S. when regulations were liberalized in the 1980s. Thus what would be needed is government incentives for competition together with regulations to require open architectures. That might be difficult to obtain, especially since it is precisely this combination that is seen as having brought about the telecom crash.

Even if governments take a hands-off attitude, or promote closed architectures, there are other restraining influences. One comes from the fact that content is not king [52]. Much of the inspiration for network designs has traditionally come from the myth that content (in the sense of material prepared by professionals for wide distribution, such as movies, or professional sports team performances) is where the money is. (Just consider the asymmetric bandwidth of cable modem and DSL residential broadband links.) But in fact there is far more money in providing basic connectivity. That is what people have always valued far more, and have been prepared to pay more for. (The far greater revenues of cellular carriers in the U.S. than of cable TV providers is just one example of this phenomenon. For more data and arguments, see [52].) But while content delivery does lend itself to a closed network, connectivity does not. Open networks are likely to win because they can attract more revenues from users.

Closely related to the false myth that content is king is the preoccupation with real-time streaming multimedia transmission. That is what the networking industry has been aiming at for decades. Yet simple projections (as well as evidence of actual usage) show that file transfers are likely to dominate [50, 69]. (This had been predicted by George Gilder even earlier. Moreover, this dominance has already occurred, even though the industry appears to be unaware of it or its significance. While MP3 file downloads using various P2P services are a huge factor on practically all networks, streaming traffic is tiny.) But in an environment where most of the traffic consists of file transfers, the typical methods being planned for controlling networks do not work well. On the other hand, such an environment does offer a promising future for service providers. If real-time streaming multimedia were to dominate, they would face a bleak future. As soon as residential connection speeds reached a few tens of megabits per second, there would be nothing new for them to offer in terms of basic connectivity. However, when file transfers dominate, and faster than real-time transfers of videos is what matters to users, service providers can keep endlessly upgrading their customers' connections, and use increasing speeds as a market segmentation device. The significance of the low utilization of data networks [48, 50] is that what matters to users is not getting lots of bits, but getting a moderate amount of bits quickly, in other words low transaction latency. What this says, in effect, is that the networking industry is trying to do differential pricing in the wrong way, along the wrong dimension. Eventually they will learn the error of their ways, but it might be a long time until they do.

There are some other factors that argue for a comparatively open network. The increasing heterogeneity of the telecommunications network (as well as its increasing importance) will mean that users will be able to mitigate restrictive practices by bypassing service providers, as large enterprises are beginning to do by buying their own fiber. This bypass strategy will be facilitated by the general migration of costs and complexity to the edges. The rapid advances in fixed wireless threaten to make fiber-to-the-home unnecessary [58], and also to destabilize what might have developed into a cozy duopoly of DSL and cable modem providers. It will not be necessary for fixed wireless to grab the lion's share of the Internet access market. It will suffice if it has a small share, but is available a viable alternative to DSL and cable modems. (The much better scaling properties of wireless, without the huge initial costs that are proportional to the number of potential customers, as opposed to actual ones, are what makes this disciplining role possible.) We are likely to end up with a system like the multi-modal transportation system of today, which is rife with discriminatory practices (just think of the variation in prices by household moving companies), but where such practices are limited to a tolerable degree.

A key distinction between the Internet and the transportation systems discussed earlier is that in transport, most of the costs were associated with the core of the network. On the Internet, on the other hand, the complexity, costs, and therefore revenue opportunities are largely at the edges. It is hard in such a situation to design a network architecture that will provide necessary controls for carriers. Furthermore (and this is very important in view of the discussion in the next paragraph), transportation charges tended to be levied relatively infrequently, on the carriers, and less so on end users,

Yet another distinction is that in transportation, the nature and value of goods does not change very rapidly. In the new economy with extensive information goods, though, that is not the case.

Perhaps the most potent limitation on the proposed new architectures for the Internet, and the associated discriminatory practices, is posed by a range of factors deriving ultimately from behavioral economics. People react extremely negatively to price discrimination. They also dislike the bother of fine-grained pricing, and are willing to pay extra for simple prices, especially flat-rate ones. Furthermore (and this is specific to telecommunications and other information goods industries, and does not apply to transportation), technology is rapidly increasing available bandwidth, so the primary imperative for service providers is to persuade their customers to increase their usage. (The suggestion in [58] that telecom service providers buy out music studios and offer recorded music for free with their broadband connections was only slightly tongue-in-cheek. The reviled peer-to-peer traffic is a major stimulant of the demand for broadband.) Constraining architectures and pricing structures work against increased usage. For more details, see [26, 51, 53], and (for a short version with pointers to the literature) [56]. The general conclusion of [51] was that price discrimination and fine-grained pricing are likely to prevail for goods and services that are expensive and bought infrequently. For purchases that are inexpensive and made often, simple pricing is likely to prevail. And we see these trends in the history of transportation. For example, as is detailed in [62], in the first half of the 19th century, railroads in England were limited in attempts to practice explicit price discrimination by law and lack of proper technology (such as the positive passenger identification that airlines rely on today). Hence they resorted to extreme forms of versioning, running third class passenger cars without roofs, and sometimes even without seats. These practices led to the famous 1844 law that forced the railroads to run the so-called "Parliamentary trains," something they did only under duress and with loud protests. This was in the early days of the industry, when railroad travel was rare and expensive. By the end of the 19th century, the overwhelming majority of passengers traveled in 3rd class cars, which by that time were much more comfortable. (And even then, just as today, operators had great difficulty figuring out how their business was evolving. As was noted by an observer in 1885, at that time "[r]ailway managers had not yet discovered that third class traffic was their main stay," p. 100 of [12].) Now the Internet already pervades society, and will be even more ubiquitous in the future, used round the clock in a variety of applications. Simplicity is likely to be key to acceptance. We see this phenomenon in operation today. Although hotels, golf courses, and other service providers are rushing to imitate airline yield management systems, many are discovering that this is not necessarily the way to riches. For example, Amtrak, after extensive experimentation with complicated pricing, has decided to pull back to the traditional approaches of simple and stable fares [40]. Hence telecom service providers are likely to discover that the elaborate architectures they are dreaming of will work against their interests.

The general conclusion then is that the historical record of the transportation industry does demonstrate the importance and prevalence of discriminatory policies that are incompatible with the basic architecture of the current Internet. This probably accounts for much of the push to build new networks, or modify the current ones so as to provide more control for service providers over what customers do. However, the Internet is special, in its importance as an enabler for the rest of the economy, in its migration of costs and capabilities to the edges, in its primary value being in connectivity and low transaction latency, and in its pervasiveness and frequency of use. Hence in spite of the strong push from the industry, there are good prospects that the open architecture of the Internet will survive.

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