# Complexity of Internet Interconnections: Technology, Incentives and Implications for Policy[1]

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## Abstract

End-to-End (E2E) packet delivery in the Internet is achieved through a system of interconnections between heterogeneous entities called Autonomous Systems (ASes). As of March 2007, there were over 26,000 in use [ASN07]. Most ASes are ISPs, but they also include enterprises, governmental or educational institutions, and increasingly large content providers with mostly outbound traffic such as Google, Yahoo, and YouTube as well as overlay content distribution networks such as Akamai and Limelight [CLA05]. Each AS controls or administers its own domain of addresses but ASes must physically interconnect to provide end-to-end connectivity across the Internet. Interconnection is not only important from a reachability perspective but also quality and performance perspective, because how ASes interconnect, both physically and contractually, determines how packets are routed and impacts the quality and choice of services that may be supported.

The initial pattern of AS interconnection in the Internet was relatively simple, involving mainly ISPs with a balanced mixture of inbound and outbound traffic. One goal of this paper is to demonstrate how changing market conditions and industrial organization of the Internet have jointly forced interconnections and associated contracts to become significantly more diverse and complex than is commonly understood. The diversity of interconnection contracts is significant because efficient allocation of costs and revenues across the Internet value chain impacts the profitability of the industry. However, current models of interconnection ([LAF03,GRE05,STA01]) fail to reflect such emerging diversity of possible interconnections. We currently lack good data and models on these developments. In particular, most models of AS interconnection describe two sorts of arrangements: *transit* (a "vertical" relationship where small networks pay larger network for access to the rest of the Internet) and *peering* (a "horizontal" relationship where similar sized networks engage in revenue-neutral interconnection). We will highlight the now obvious distinction between networks that specialize in content distribution and broadband residential networks that specialize in consumer access to the Internet. The introduction of such ASes increases the heterogeneity of players in the interconnection market. Furthermore, their highly asymmetric pattern of traffic flow (from content to "eyeballs") has resulted in increased complexity of the incentives to interconnect, and the diversity of the resulting negotiation.

Not surprisingly, the challenges of recovering the fixed and usage-sensitive costs of network transport have given rise to more complex settlements mechanisms than the simple bifurcated (transit and peering) model. In the following, we provide insight into recent operational developments, explaining why interconnection in the Internet has become more complex, the

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nature of interconnection bargaining processes, the implications for cost/revenue allocation and hence interconnection incentives, and what this means for public policy.

# 1 Introduction

The Internet was designed so that different providers could operate different parts of the network. Today, the Internet is built up out of regions, or Autonomous Systems (ASes) that include commercial Internet Service Providers (ISPs), corporations and other enterprise providers, universities, government agencies, and (more recently) content providers and other specialized service providers. This design results in a network of networks that, like any distributed supply-chain, requires competitors to cooperate to deliver a coherent end-to-end service. In today's Internet this state of "coopetition" takes the form of rich interconnection among ASes such that networks carry each other's traffic to reach final destinations.

In the beginning, the pattern of AS interconnection somewhat resembled a simple hierarchy, with campuses and other geographically local networks connecting to regional networks, and the regional network connecting (in the U.S.) to a single government-subsidized NSF backbone. The pattern of interconnections that emerged in the commercial Internet in the mid-1990s is relatively more complex, comprised of many networks connected among themselves and to multiple interconnected backbones (so-called "Tier 1" providers, as we will define below), governed by market-based contracts that are negotiated on a bi-lateral basis. This evolution was enabled by infrastructure innovation toward higher capacity switching and transmission links and new routing protocols.

The pattern of interconnection may be viewed conceptually as the result of a complex, dynamic bargaining game between pairs of ASes. The outcome of this bargaining game is important because the choice of interconnections determines not only reachability but also performance features such as the scope of routing capabilities (e.g., how many diverse routes are available and the quality or congestion experienced along those routes). However, these bargaining games are fraught with potential breakdowns due to either transaction costs and/or agency/opportunism problems. For instance, perhaps more so than in many other industries, it is often unclear who should pay whom for interconnection on the Internet.[2] It is not possible to deduce the direction of "value flow" by looking at the direction of packet flow: if A sends a packet to B, did A or B benefit from this transfer? Even if there is no bi-lateral ambiguity of who should pay whom there are no explicit *end-to-end* signals of value flow in the Internet mechanisms raising the transaction costs of coordinating and internalizing complex value flows. This is in contrast to the telephone system, which traditionally had two sorts of calls (normal, or sender pays, and "800 calls", or receiver pays).

[2] An obvious further economic rationale for the ambiguity of "who pays whom" is the ubiquity of shared/common infrastructure/costs that characterize the Internet. When costs are common to more than one activity (e.g., cost of feeding a steer is to make meat or leather?), economics does not provide a priori grounds for determining appropriate assignment of costs. The Internet grew incrementally and virally, as an application on top of an already existing physical "telephony" network -- the Public Switched Telecommunications Network (PSTN) – that was largely put in place, regulated, and paid for without reference to the Internet. Of course, because the Internet has grown substantially and is now "the platform" for our PSTN, the magnitude of and diversity of costs that must be recovered are substantially larger and more complex.

Given the simultaneous benefits of interconnections, two simple uniform/standardized types of bilateral mechanisms or contracts[3] for AS interconnection emerged in the early commercialization of the Internet: *peering* and *transit*. A *peering* agreement (also called "Bill and Keep" or "Sender Keeps All") is where two networks provide access *only* to each other's customers for no financial settlements. In contrast, *transit* is where one network provides reachability to the *entire* Internet in return for a monetary settlement.[4] The recursive combination of these standardized bilateral peering and transit contracts created the complex web of interconnections wherein networks become resellers of transport and peer with one another in what has been a mutually beneficial and hence largely stable manner.

Previous academic work on the incentives of network operators to interconnect has focused either on *direct* externality effects [NUE05] or agency models [MIL00]. In contrast, this paper focuses on the emerging interconnection bargaining practices involving heterogeneous ASes. These contracting developments will be framed within the context of the historical and emerging industrial organization of the Internet, showing how entry by new types of content providers and distributors have transformed and constrained the bargaining game that supports global connectivity. The goal of this paper is to provide an insight into this rich and complex operating environment, to suggest some of the ways that interconnection is changing and will continue to change, and to trace the implications for Internet architecture, industry structure, and public policy.

We will focus on a single Internet service, namely content (web) delivery: first, because content accounts for a large portion of today's Internet traffic and second, because interconnection and settlement mechanisms and strategies are being increasingly influenced by the emergence of large sources of web content and very large aggregators of residential broadband customers -- the DSL and cable ISPs, each with very asymmetric patterns of traffic (almost all traffic is outbound from the server and inbound to the consumer). These large networks are substantial-enough players that their interests are changing Internet interconnection bargaining processes and giving rise to new contracting variants such as paid-peering and partial transit. We will also show how a system limited to bilateral transfers fails to send relevant price signals that can be used to internalize potential *indirect* externalities across complementary distinct markets, leading to closure of viable markets. This market failure is partially responsible for the entry by third-party application layer content distribution networks, and other overlay models of content delivery.

The paper is organized as follows. Section 2 introduces some useful interconnection definitions that will be used throughout the paper. Section 3 then provides a brief overview of the history of interconnection, focusing on the adoption rationale for existing contracting mechanisms (peering and transit). The rationale and emergence of new contracting mechanisms is then reviewed in Section 4.[5] Sections 5 and 6 then present abstract and concrete instances of strategic components of peering bargaining games respectively. Section 7 then provides a brief overview of end-to-end inefficiencies of bi-lateral bargaining, and demonstrates how such failures have resulted in potential market failures and provided entry incentives to third-party content distribution networks, in response. Section 8 closes with a summary of our conclusions and implications for public policy.

[3] Throughout the text we will refer to "mechanism" and "contract" interchangeably

[4] These contracts are defined more formally below.

[5] Further details on the structure and costs of interconnection are explained in an Appendix.

## 2 Definitions—Settlement-Free Peering and Transit

In order for us to discuss the range of interconnection arrangements that have now emerged in the current Internet, we need a careful definition of some commonly used terms. This section will provide those definitions, and try to provide a description of peering and transit.

The entities that are interconnected are referred to as Autonomous Systems (ASes), defined as:

> ***Definition*** **(*AS*)**: An Autonomous Systems (AS) is the unit of administrative policy, either a single network or a group of networks that is controlled by a common network administrator (or group of administrators) on behalf of a single administrative entity (such as a university, a business enterprise, or a business division).

An autonomous system is also sometimes referred to as a routing domain. Many AS numbers are associated with commercial Internet Service Providers (ISPs), and we will often refer to an ISP rather than to an AS when the commercial actor is the obvious example of what we are discussing. An autonomous system is assigned a globally unique number, sometimes called an Autonomous System Number (ASN).

Each AS will have been assigned one or more blocks of *Internet addresses* by the Internet Assigned Numbers Authority (IANA). Generally, bigger networks are assigned large blocks of addresses. Internet addresses are 32 bit numbers, often written as four digits, each representing 8 bits of the address: for example 18.26.0.36, where 18 is the decimal representation of the first 8 bits, and so on. A block of addresses will have a common first part, or *prefix,* and the prefix defines and describes the block. In the case of 18.26.0.36, this address belongs to MIT (which has ASN 3) and the MIT AS controls all the addresses of the form 18.xx.xx.xx.

> ***Definition*** **(*Prefix*)**: A prefix is a group of IP addresses on the Internet that have some number of the first bits of the addresses in common.[6]

Internet routers keep tables that let them forward traffic to all known public IP addresses.[7] For scalability reasons, the routers do not have a separate forwarding entry for each known IP address but keep track of information at the level of prefixes. The Border Gateway Protocol (BGP) is used to distribute information about these prefixes among the various ASes of the Internet, which the ASes then use to forward packets.

How might one AS (for example, AS A) get access to the entire Internet? One way is for ISP A to enter into an interconnection relationship with some other ISP (for example, X) where X agrees to tell the rest of the Internet about "where" A is (which is called "announcing its prefixes"), and to agree to send and receive traffic between A and the rest of the Internet. This form of agreement is called *transit,* and is equivalent to saying that "A is a customer of X".

X either has access to all global Internet addresses or else in turn purchases access from another AS that has a more extensive access. Each AS will have been allocated one or more address prefixes for its use, but if it provides transit service to another ISP, it must also take responsibility for announcing the prefixes of its customers. This relationship is recursive. A small AS A could

[6] The prefixes (the part of the addresses that are the same) can be different for different address blocks. MIT owns all of the addresses of the form 18.xx.xx.xx. This is a large address block. An example of a smaller block would be 128.30.xx.xx.

[7] There are also addresses that are private, which means that they are not listed in the forwarding tables. They might be found behind NAT boxes, in enterprise intranets, and so on. We do not consider these further.

purchase transit service from a medium sized AS M, which in turn could purchase transit service from X.

> ***Definition*** **(*Cone of Prefixes*)**: For any AS, its cone of prefixes refers to addresses that terminate either in that AS or on other ASes that it has sold transit to (which recursively includes any addresses of customers of those ASes, and so on).

If A purchases transit service from X, then A can have a very simple forwarding table. It needs only two classes of AS-level entries: its own prefixes and "everywhere else". For its own prefixes, it will use its intra-AS routing protocols to forward the packet internal to the AS.[8] For "everywhere else", it just sends the packet to X. This sort of forwarding entry is called a "default route". When A purchases transit from X, X must make sure that all the ISPs know that X is the path to the prefixes of A, but A need not concern itself with where all the other prefixes are. It just sends the traffic to X.

> ***Definition*** **(*Default Route*)**: The Default Route allows a router sends packets for which it does not have specific instructions.

Network A can purchase transit from network X, but what does X do to reach *all* of the Internet? There are only two possibilities: either X purchases transit from yet some other provider, or it enters into some other sort of interconnection arrangements to reach the other parts of the network. The other arrangement that is used for this purpose is called *peering*.

Imagine that there are two large providers of Internet connectivity, X and Y. X has its set of customers, with its cone of prefixes, and similarly Y has its cone of prefixes. In a peering agreement, X and Y interconnect, but only for the purpose of providing a path between the two cones of prefixes. In the original model of peering, called *settlement free peering*, there was no payment between X and Y for this arrangement, but the configuration of the forwarding is independent of the arrangement for payment.

There is a set of ASes that do not purchase transit from any other AS: these are called *Tier 1* ASes. Since a Tier 1 AS does not purchase transit, it cannot take advantage of a default route; it must peer with every other Tier 1 AS, so that it gets access to every cone of prefixes in the Internet.

> ***Definition (Tier 1 AS):*** A network that does not purchase any transit service, nor make use of any default routes, peers with every other Tier 1 AS and pays no settlement on their peering agreements is called a *Tier 1 AS*.

> ***Definition (Default Free)***: A network is default free if its routers have no Default Routes in its forwarding table. ASes that are Default Free must assemble a Global Routing Table based on information obtained from its peers (using the routing protocol BGP).

> ***Definition*** **(*Global Routing Table*)**: A Global Routing Table lists every single prefix on the Internet, the different available paths to that prefix, and other information that lets the AS make forwarding choices based on the available paths. Such a table is also called a *default free* routing table, because it contains an explicit entry for each prefix, not a default route to a set of prefixes. Each AS will have a different GRT, since each AS will have different paths to given destinations.

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[8] Internally, an AS may do a number of things like offer specialized quality-of-service routing to support services like virtual private networks (VPNs) or offer differentiated treatment for applications with different delay sensitivities such as VoIP or email traffic.

To get an idea of the size of the routing table for a Tier 1 provider, today a Global Routing Table includes over 26,000 ASNs and over 230,000 prefixes.

## 2.1 End-to-End Packet Delivery through Peering and Transit

Since a Tier 1 ISP must peer with every other Tier 1 ISP, the set of Tier 1 ISPs form a complete mesh of peering arrangements. Tier 1 ISPs are large, with global scope. They do not peer at only one physical location, but typically at a number of points around the globe. This makes the management of the peering relationship operationally complex. Most often, the sending ISP chooses to get rid of the packets as soon as possible, so that the receiving ISP internalizes the majority of total costs of delivering the packet. The strategy of handing off the traffic as soon as possible, at the peering point closest to the source, is sometimes called *hot potato* routing. Hot potato routing sheds the majority of the total end-to-end delivery cost to the receiver of packets, lowering the cost to the sending ISP.

All Tier 1 ISPs must peer with each other, but the use of peering is not restricted to Tier 1 ASes. Any two ISPs can choose to peer with each other, by mutual agreement. Two small ASes that discover that they have a lot of traffic for each other might decide to create a direct peering connection rather than sending the traffic up to their transit providers, which would increase the load and thus (often) the cost of their transit service. There are a large number of reasons why two ASes might choose to peer, and it is this bargaining over whether and how to peer that we explore in this paper.

Any AS can choose to purchase transit from more than one provider. They might do this, for example, to obtain more diverse and resilient access to the Internet (called *multi-homing*). When an AS does this, its addresses become part of the prefix cone of all of their transit providers. So the addresses in the various prefix cones that are attached to the different Tier 1 ISPs are not strictly disjoint, but contain overlapping entries.

If a given AS A is multi-homed, then as BGP propagates the information about how to reach A to other ASes, those other ASes may discover that they have multiple routes to A. Each such AS must then make a choice about which route to include in its forwarding table. It might make this choice based on performance, reliability or other factors, but in fact most such choices are made based on the relative cost and business implications of the various options.

# 3 History of Internet Interconnection

Historically, the major distinction among different ISPs was their size. Size could be measured in a number of ways: geographic scope, total rates of traffic across the boundaries, or the number of attached customers. The size and number of announced address prefixes could also be used as a proxy for the number of active users or the anticipated levels of cross-border traffic. Although ISPs differed in size and coverage area, most were approximately similar with respect to the types of services they offered and (size aside) with respect to their incentives to interconnect. These relatively symmetric incentives to interconnect were important in defining the nature of the interconnection bargaining game that emerged in the early days of the commercial Internet.

The idea of symmetry among ISPs of similar size emerged as follows. In the backbone, the presumption of symmetric costs among approximately symmetrically sized "peers" meant that when network A delivered a packet received from network B to customers in its cone of prefixes, it was reasonable to believe that the costs of that delivery were approximately similar to the costs incurred by network B when it delivered a packet received from network A to customers in its cone of prefixes. If the costs are similar, the traffic is balanced and by some estimate the networks host equal numbers of users, then it could be argued that the benefit of interconnection was similar to both parties. Second, since the costs of constructing and operating a data network are mostly traffic insensitive (and associated with maintaining the network's peak load capacity), the incremental costs of delivery were presumed to be relatively small. In conjunction with the first point, this implies that total network costs could be reduced if usage-sensitive metering were largely dispensed with, resulting in settlement free (revenue neutral) peering among *similar sized* backbone providers.

In contrast, the assumption of symmetric delivery costs seems less applicable when a large network exchanges traffic with a small network. In an uncongested state, a typical packet that originates on a network with smaller geographic scope and ends up on the larger network might be expected to impose higher delivery costs on the larger network (which must typically carry the packet a greater distance). A larger network would presumably have more customers, and this might be seen as giving the larger network more value because of the larger positive network externalities associated with being part of their networks. Taken together, these effects may have contributed to the perception that size contributed to a network's bargaining position.[9] In any case, smaller networks tended to negotiate transit agreements with one or more larger providers under which the smaller networks agreed to pay the larger providers to deliver their traffic. In this earlier world of peering (among networks of the same size) and transit (between large and small networks), there were ASes that differed principally with respect to size, but in other respects were remarkably similar and symmetric in their overall incentives and view of the interconnection problem.

## 3.1 Transit and Peering Bargaining Process

We will now explore some of the considerations that shape the transit and settlement-free peering bargaining, looking first at the historical patterns of transit and revenue-neutral peering. We will look both at the (transaction and agency) considerations that arise before an agreement is reached (*ex ante),* and those considerations and actions that arise after the contract is in place (*ex post)*.

### 3.1.1 Full Transit Interconnection

Full transit is the most common type of interconnection agreement used in the Internet. Most small networks or enterprise customers may have a single full transit agreement as the single means of interconnection to the Internet. Larger networks may connect to multiple transit providers.

In most cases, the structure of full transit settlements is usage based, commonly implemented as a "95$^{th}$ Percentile", or "95-5" rule.[10] The customer (A) of such a contract commits to and pays provider (X) for a level of total traffic network A will send *or* receive to/from its provider (called the Committed Information Rate, CIRs, which is measured in Mbps) *ex-ante* before the actual traffic load is realized. The provider AS then computes the rank ordered 95$^{th}$ percentile of the inbound traffic and the outbound traffic and typically selects the maximum of the two values (or less commonly takes the average or sum) as the traffic load for the month *ex-post*. If it is above

[9] The relative strength of the bargaining position of ISPs, even in the early days, was ambiguous with respect to size. While the positive network externalities associated with joining a large network are larger in aggregate, there were many backbone providers and the incremental benefits of larger size decrease with size. In section 4 we discuss the apparent shift in the bargaining positions over time.

[10] These percentiles are based on making measurements over pre-agreed time increments (e.g., five minute intervals) of total traffic flows and these are then ranked in descending order to provide a measure of capacity utilization over time (by tracking peak flows).

the CIR the customer is priced according to an *ex-ante* mutually agreed excess tariff rate. While there are networks that sell flat-rate links, those types of full transit contracts are relatively less frequent, especially for larger capacity circuits. Generally, full transit pricing is subject to substantial volume discounts (i.e., the per Mbps price declines steeply with the CIR and actual traffic load). To get an idea of what levels of transit pricing look like (while recognizing that the variation in what ISPs pay varies widely across agreements and around the globe), the table below summarizes data gathered from a sample of 42 ASes in 2006:[11]

| Survey Sample Size | 42 |
|---|---|
| Average Monthly Price | \$25/Mbps |
| Maximum Price | \$95/Mbps |
| Minimum Price | \$10/Mbps |
| Average Commit Levels | 1440 Mbps |

**Table 1: NANOG 2006 Transit Survey (Source B. Norton)**

Transit contracts are enforceable and the customer usually receives a service level agreement (SLA) to ensure appropriate quality of service and reliability. This will include commitments to repair and restore service after failures, as well as performance commitments under normal operation.

### 3.1.2 Settlement Free Peering Interconnection

As we have said, peering is when two networks agree to exchange traffic destined for the other's customers in a settlement free manner. That is, network A will announce to network B all of its cone of prefixes, the prefixes for which it is responsible (all addresses that are on A or on networks that A has sold transit to), and B will announce to A all of the prefixes in its cone of prefixes for which it is responsible (all addresses that are on B or on networks that B has sold transit to). In settlement free peering, traffic is exchanged without any payment. After transit, this is the second most common form of interconnection in the Internet. Tier 1 networks peer with each other to form a default free (see section 2, page 6) fully connected mesh. For a Tier 1 a full mesh is *necessary* for the transit service they provide all other non-Tier 1 ASes. A packet has to eventually be handed-off to some AS who knows the prefix address of the final destination. Either there is one such AS who stores such a global routing table (the previous NSFNet, with associated congestion and structural problems) or there are multiple ASes that can reach every address in the Internet through collectively peering with one another. Non-Tier 1 networks may also elect to peer, not for necessity but for optimization purposes. The advantage of settlement free peering to a non-tier 1 is that it can offer a lower cost alternative to any network that might otherwise have to pay transit for the traffic that it exchanges via a peering arrangement.

However, because peering is cost saving it exhibits a number of *ex-ante* (see NOR03) and *ex-post* opportunism/agency problems (see [MIL00]). Therefore there are often peering requirements (stated in publicly available peering policies, see [PPO07]) of various strengths including:

- *Geographic Diversity:* Many networks require potential peering partners to set up links in multiple, geographically diverse locations. For instance, a US national network may

[11] This data was collected by B. Norton in 2006 from 42 surveyed ASes at the 36th Peering Bird of a Feather at North American Network Operator's Group (NANOG). See [NOR06] for the reported nonlinear pricing reported.

require a minimum of three peering links, including east coast, west coast, and central. Very large networks may require peering links on at least 3 continents, as well as multiple locations in each continent.

- *Traffic Volume:* If A requests settlement free peering from Z, Z will measure its traffic to/from A. If the volume is small, Z will deny the request. The traffic volume requirement in each network's peering policy is usually based on the size of the network. For very large networks, the traffic volume requirement is measured in gigabits per second.[12]

- *Traffic Ratio:* In settlement free peering relationships with very large networks, there is frequently a requirement to keep traffic "in ratio". The traffic going from A to Z is measured, and the traffic going from Z to A is measured. If the two numbers are not close enough, peering will be denied. For very large networks, the traffic ratio requirement is usually 2:1, and sometimes 1.5:1. The nominal rationale behind traffic ratios is cost sharing. In part, because "hot potato routing" is common practiced on the Internet, and as mentioned above involves the sender opportunistically allocating the majority of the total end-to-end delivery cost to the receiver, two peers can have very different costs. This problem can and has been solved many times, through mechanisms such as cold potato routing, partial announcements, and local caching. But many broadband providers use the ratio requirement to disqualify peers.

- *Consistent Announcements:* Most networks require peers to maintain consistent BGP announcements across all peering links. This simply means that the BGP announcements should be identical, modulo irrelevant location-specific details, on every BGP session between the two networks.[13]

- *Marketing considerations:* Many ISPs will refuse to peer with an ISP that is a customer or a potential customer, as we discuss below.

- *Other Requirements:* In the early days, since revenue-neutral peering did not involve payment, many sales and marketing departments of ISPs did not pay attention to the issue of peering, and peering arrangements were set up by the engineering staff of the two ISPs, based on traffic data that suggested to them a mutual cost-savings. In these cases, there might be no formal document describing the terms of the arrangement, just a hand-shake and a wire. In other cases, peering was seen as an important strategic tool, and ISPs would put forward complex and sometimes onerous peering requirements, which few potential peers could meet. Today, peering policies for very large networks have multiple requirements which are difficult or even impossible for small networks to fulfill. These requirements have changed over time, becoming more onerous, and thus reducing the likelihood that smaller networks will be able to peer with larger networks. For instance, very large networks may require prospective settlement free peers to have certain sized links in their backbones, provide transit to a certain number of prefixes or AS numbers, or not be a customer of the larger network. Lastly, most very large networks require both companies to sign a peering agreement. This is a contract listing all the requirements, and

[12] To provide some context, typical peering connections today are 10 Gbps. In 2000, OC12 was common. In 1995 a peering link might have been 10 Mbps ethernet or DS3.

[13] Consistent announcements allows a peer to hot potato traffic, inconsistent announcements force a peer to cold potato traffic. Assume A and B peer, and A only announces west coast prefixes on west coast peering points, and the same for east coast. If B has a packet in New York for A, B must carry the packet to the west coast where B sees the prefix announced. If B is announcing consistently to A, A can pass the return packets to B on the west coast. This shifts costs from A to B.

consequences should a requirement not be fulfilled. Peering agreements seldom have any provisions that are enforceable by any means other than termination of the contract. Since this is essentially the same recourse when there is no contract, the overwhelming majority of smaller networks do not require a peering agreement.

### 3.1.3 *Ex post* Issues

As we noted, some peering agreements are very informal, with no real terms and conditions to regulate the relationship. Others may be more formal. In both cases, a very important issue is what one partner can do if the arrangement is not working out as they want, and they need to withdraw or renegotiate. For example, what can one ISP do if traffic from the other ISP is not conforming to the required in/out ratios, or is not meeting the minimum volume requirements? Because traditional peering arrangements did not include payments, they also did not contain financial penalty clauses for non-performance.

One drastic recourse is for one side to disconnect or *de-peer* the other. However, such action usually takes the form of a game of "chicken". If A de-peers B, B will lose access to the cone of prefixes of A, unless both networks have a suitable transit arrangement as backup. So it may be the case that the customers of A are more inconvenienced than the customers of B, and as well that B can make loud public protest that A has exercised its market power to harm B.[14]

Given that de-peering may be a path to mutual harm, ISPs are seeking less drastic remedies for non-conforming peering arrangements. For example, if the traffic ratios become imbalanced, and A is delivering too much traffic to B, while B has little traffic for A, B might demand, as a condition of continued peering, that A employ "Cold Potato" routing by which A carries the traffic across its own network as close to the destination as possible, and hands it off to B at the peering point closest to the destination, to minimize B's costs. This is opposite of the hot potato routing we discussed earlier.

While these sorts of technical options are in play today, it is becoming more common that the remedies are financial, pricing the residual costs. If the two parties have an actual contract, with formal terms, then the remedy for non-conformance is pre-negotiated *ex ante* and B just sends A a bill. This idea opens up a much broader line of questioning—perhaps the basic peering agreement should involve a financial component, rather than being free. Why is "revenue neutral" the default presumption? This line of thought has two implications—more formal peering contracts and the emergence, as we will discuss below, of *paid peering.*

## 3.2 Value-Internalization and Cost Trade-Offs

Whether peering or transit, the focus of the negotiation was historically volume and destination based value-accounting and contracting. This contracting regime arose in the context of the single-service class best-effort Internet architecture, motivated primarily by technical desiderata of scalability, resilience and convergence, and the lack of technical means to enforce or implement other sorts of arrangements. The bilateral volume of traffic exchanged and address space size are often used as a proxy of value flow because they can be monitored, verified, and accounted for with relatively low transaction costs. Consequently, net aggregate packet flows and addressable address space (the size of a Tier 1 network's cone of prefixes, for example) were the focus of early interconnection agreements.

[14] See [LEV05,UND05] for an illustration of rationale, technical and consequences this sort of dispute.

However, this simple approach to approximating value masks a number of considerations of practical importance to operators today. For example, ISPs may value not only the size of the address space, but also the type of application traffic which another ISP carries, especially as packet transport is increasingly viewed as a commodity service. Delay sensitive content providers may value lower latencies more than networks focused on single class best-effort packet transport. Ambiguities of who should pay whom further increases with the obvious breakdown of the "symmetry assumption", as we will discuss below. Furthermore, even if value transfer is not ambiguous there is currently no technical mechanism for end-hosts to signal to the network their willingness to cross-subsidize the transport costs of the other end-hosts. As we noted, the Internet, unlike the telephone network, does not have a 1-800 number to support "receiver pays" data transport.

In sum, such bilateral constraints -- due in part to the limitations of legacy interconnection regimes because of the architecture -- conceal end-to-end value information that might otherwise provide the basis for signaling the magnitude and direction of direct and indirect externalities. The lack of such an appropriate signaling mechanism may result in the foreclosure of markets for certain services (e.g., QoS differentiated services for the general Internet). Historically, this potential loss was traded off against the benefits of lower uncertainties associated with the simpler interconnection environment. Volume and destination-based value accounting resulted not only from architectural constraints,[15] but were also a "satisficing" response to residual uncertainty of who should pay whom. Other value proxies would have introduced higher uncertainties and bargaining costs.

# 4 The erosion of homogeneity

Over time and with the growth of Internet traffic, the idea that ISPs of a certain size (as we defined it above) were more or less the same has broken down. We have seen the emergence of new types of providers, which we will call (to over-simplify) *content* networks and *eyeball* networks. Content networks are typified by ISPs such as Abovenet and Cogent that host a great deal of content and by larger content providers such as Google and Yahoo -- *application* layer entities with large asymmetric traffic patterns. A web browsing request involves a small amount of data being sent to the content server, and in response, substantially more data being returned back to the user who submitted the original query. The end-users who are submitting the queries are located on "eyeball" networks (such as Verizon or Comcast). The "eyeball" customers want the content since that is part of the reason they pay for broadband service; the "content" networks need the eyeballs because that is what they sell to advertisers and the "eye balls" are the end-users who may subscribe directly to pay-to-view content. Thus, there are demand complementarities across distinct and asymmetric end-host markets who are customers of ASes. Such markets also exhibit strong *indirect* externalities, where consumption by one side of the market increases (often non-linearly) as the consumption of the other market grows. The question of who should pay whom to recover the costs of supporting that interconnection is ambiguous in this asymmetric world.

We observe in practice that most content-heavy networks are more open in their peering policies than are most eyeball-heavy networks (see [PPO07]). We can speculate on a number of reasons for this difference:

- As opposed to early access networks where switching costs for consumers were insignificant (because they could call any local modem bank ISP), modern broadband

[15] See [HUS99a,b] for further discussion of how architectural constraints limited the range of settlement mechanisms.

consumers may feel that switching costs are relatively higher. Therefore eyeball networks perceive that they may have some increased bargaining power because they "own" the eyeballs. If the end-users on a particular network are sufficiently attractive to reach, then even a small network may be in a relatively advantageous position with respect to negotiating interconnection with content providers.[16]

- Eyeball networks believe that the "natural" direction of *value* flow is toward them, rather than away from them. While it may not have been obvious in the early days of the Internet whether value flowed in the direction of the packet flow, or in the other direction, the emergence of the commercial Internet with high-volume, high value (e.g. with advertising) content has triggered a pragmatic conclusion that value flow is the same as packet flow. Money flows in at the content end (e.g. via the advertising or merchant revenues) and the content provider places more value on the eyeball than the eyeball does on the content. Whether or not all would accept this assertion, it is more and more shaping the interconnection negotiation in this asymmetric world.
- The last-mile networks of the broadband eyeball networks are more capital intensive, often involving "lumpy" investments, than are the long-haul and backbone networks of content-providers. This is because of the economics of deploying broadband last-mile infrastructure and differences in aggregation economies.[17] Consequently, the cost recovery challenge of the last-mile networks is greater (although as noted earlier, it is not clear that their incremental costs for delivery are higher).

The emergence of these new types of ASes has been referred to as the "third disruption" because the asymmetric nature of their traffic results in changed incentives for interconnection [NOR03]. Not surprisingly, the rise of large new ASes with asymmetric traffic patterns complicates the interconnection bargaining game. In contrast to the relatively simple environment that characterized the legacy interconnection environment, the new asymmetric markets are multi-sided, requiring matching of distinct markets with strong indirect externalities[18] with attendant impacts on industry growth.[19]

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[16] Note, this is an *ex-post* argument where interconnection bargaining is assumed to be conducted *after* the end-user has adopted an access provider. Normally, the interconnection bargaining game is likely to be embedded in a larger *ex-ante* game where providers compete for customers. See [AMR06, HER06] for a discussion of *ex-post* bargaining power when one side of the market is single-homed and the other-side is multi-homed.

[17] The distinction is analogous to the lower capital intensity of long distance telephone service relative to local telephone service. The fact that the long distance network shared the local access network was used to help justify long distance services subsidizing local telephone services to help recover the fixed costs (non-traffic sensitive) costs of last-mile infrastructure. For many years, long distance toll calls paid regulatory-mandated per minute access charges that significantly exceeded the usage-based costs associated with toll calling. Such implicit subsidies are inefficient and inconsistent with the transition to competition and so over time rates have been rebalanced so as to move long distance access charges closer in line with estimates of incremental costs. The subsidy for non-traffic-sensitive costs that was lost through this rebalancing of rates was partially offset by the introduction of monthly flat subscriber line charges imposed on residential and business access lines.

[18] The externalities are indirect because they refer to the growth in supply/demand for complementary goods. Thus, the growth in choice for content/applications stimulates demand for broadband access and visa versa since the "goods" are complementary.

[19] For example, see [FAR06, FAR07] for an application of two-sided markets theory to the entry and scaling incentives of Content Distribution Networks.

For these sorts of reasons, we observe that even small eyeball-heavy networks might sometimes refuse to peer with a much larger content heavy network, and this has led to the emergence of new forms of interconnection contracts. In the following sections, we describe the new and un-standardized models of interconnection that have emerged. The two new types of agreements we will discuss are paid peering and partial transit.

## 4.1 Paid Peering

Paid Peering, sometimes called "Settlement Based Peering", is identical to settlement free peering in terms of how prefixes are announced and traffic is forwarded. What differs is that the traffic is no longer exchanged without payment from one side to the other. The emergence of paid peering, although non-standardized in its details, is not surprising as a concept. If an eyeball provider is not prepared to offer settlement-free peering to a content provider, then the traditional interconnection agreements offer few options, none of which is a good solution. These include:

- If the eyeball network has a very strong bargaining position, it might try to force the content provider to purchase transit service from the eyeball network. However, apart from cost, this is not the service that the content provider needs. It does not need access to all of the Internet, but only to the cone of prefixes that belong to the eyeball network.
- Both the eyeball network and the content network can purchase transit from third parties, in which case both are *both* worse off, and the third parties are the only beneficiaries.
- If the eyeball network already peers with some third network, the content network can negotiate some sort of transit arrangement with that third network. Again, in this case, only the third network is better off.

As the eyeball network and content network bargain, paid peering would naturally emerge as an alternative that leaves both parties better off than any of these three options. If peering would indeed reduce the real costs of interconnection, and would certainly eliminate the need to pay some intermediate for transit in order to resolve the negotiation failure, then the obvious path is to see if a payment that is less than the cost of the transit payment can be negotiated for direct peering.[20]

In fact, settlement free peering arose as a defensible approximation only in the context of assumed symmetry in value flow. If the difference in actual value were small, bargaining costs would swamp the benefits of negotiating a price. However, once the assumption of symmetric value starts to break down, the binary world of transit and settlement free peering will break down. And the increasing business sophistication of the current ISPs, and their willingness to invest more in marketing and strategy relative to facilities and operations, suggests that a move to add financial terms to the increasingly complex peering agreements is both natural and inevitable.

[20] In fact, the asymmetry we describe, and the emergence of paid peering, represent a complete inversion of the circumstances that surround consumer access. In the days of dialup, many of the consumer ISPs were very small providers, literally with a modem bank in a garage. They were minor players in the business, and would connect only by purchasing transit. It is the rise of the large, broadband provider that has redefined the character of an eyeball network, shifting the expectation from paying transit to negotiating to be paid.

## 4.2 Partial Transit

The second new type of interconnection agreement that is emerging is referred to as *Partial Transit*. Partial transit relationships are far less common than full transit relationships, but are becoming more common. Under partial transit, a network Z sells access to and/or from a *subset* of the Internet prefixes to another network A: more than peering but less than all, or Z sells transit with some service restriction. For instance, Z may sell A only the ability to send traffic to part of the Internet, but not get substantial traffic from that part of the Internet. (In other words, A can behave like a content network but not like an eyeball network.) The reverse may also hold – A may be allowed to receive traffic but not send traffic. In this relationship, A will pay Z, but the price for partial transit will usually be less than half the cost of a comparable amount of full transit.

Partial transit agreements are a response to two competing commercial pressures. On one side, and as mentioned above, we are seeing the emergence of very large networks with one-way traffic (e.g. big cable or DSL providers) that have provisioned large peering or transit pipes that can handle traffic in both directions. Providers with significant amounts of in-bound traffic therefore have a strong incentive to sell the outbound capacity on links for which the set-up costs have already been committed. Partial transit can also be used strategically to help a network balance peering ratios, which is important since (as we have noted), under the terms of typical peering agreements, providers who let their traffic become too unbalanced may risk being "de-peered" or paying overage penalties.

Networks also frequently sell partial transit to give their customers access to valuable peering relationships. If M and N peer, then M might consider selling partial transit to A but only to get to N. If N has a restrictive peering policy, (so A cannot arrange to peer with N) those routes to N via M are valuable to other networks wishing to reach N. M can sell just those routes at a discounted price as a quick source of high-margin revenue. Selling partial transit to large peers may create an incentive for the peer to upgrade the peering links. In this way, the partial transit agreement operates as a form of arbitrage that expands the range of networks that may participate (even if only indirectly) in peering agreements with large providers.

At the same time that partial transit agreements are emerging, the price of full transit has been falling rapidly as a consequence of increased competition and technical innovations that have lowered the costs of terminating traffic. Falling prices for full transit will cap the incentives to negotiate more complex partial transit agreements since the relevant cost savings are smaller.

## 4.3 Summary

Taken together, the emergence of paid peering and partial transit represent a filling in of the contract space. Instead of a choice of two (relatively) standardized agreements that neatly mapped to networks based on their relative size (i.e., similar sized networks might peer, but large networks charged small networks for transit), the world is moving towards a continuum of contract types. The drivers for this include the growing heterogeneity and shear size of the Internet, as well as the bifurcation of the large networks by type as well as by size. The expansion of contract types may be viewed as a rational expansion in choice to accommodate the greater diversity of needs. This is consistent with market competition forcing participants to innovate towards more efficient cost-saving contracts. Viewed in this light, these new contracts may be interpreted as an efficiency-enhancing outcome. Paid peering allows providers who otherwise would fail to negotiate peering to better accomplish their interconnection objectives. And, partial transit represents a way to make transit more like peering, allowing flexibility in the scope of termination commitments in return for greater flexibility in payment terms as well as the benefits of enforceable contracts.

The welfare effects of these emerging contracts are nonetheless ambiguous, needing further data and models. For instance, a *possible* concern that might arise in the future is that the increased complexity of the interconnection space may raise bargaining costs, and in the extreme pose a threat for the equilibrium that has sustained E2E connectivity in the Internet thus far. To understand how this might arise, consider that the new contract forms increase the flexibility with which the design of the web of interconnections may allocate network costs. For example, consider a network with multiple paid peering and/or partial transit agreements, each of which may have very different payment terms and hence cost implications for the various networks. These agreements and the cost structure they imply will be private information of the networks and may be only loosely (if at all) linked to the underlying traffic patterns or infrastructure costs that motivated the negotiation of the agreements in the first place. Remember that in bargaining, any price between the seller's willingness to sell and the buyer's willingness to buy is a potential equilibrium – which is distinctly different than the law of one price that prevails in traditional commodity markets. Because interconnection agreements are negotiated over time, there could be a random dispersion of interconnection payments that would serve to obscure underlying incremental costs, and hence, the markets ability to move to an efficient equilibrium.

An alternative interpretation argues that these contracts must be welfare enhancing and proceeds as follows: If these emerging contracts are self-enforcing then they *must* have more value than costs. Furthermore, even if their costs do increase to the point where they are too prohibitive, then the outside bargaining option is no longer disconnection, as previously, but rather implementation of current transit and peering contracts. If we are observing these new contracts it must be either that: a) all players are better off than before or b) players are irrational according to economic theory.

The welfare effects of these emerging contracts are therefore ambiguous, and while various of the authors might be attracted to one or another of these speculations, they are indeed speculations, and need further research. Whether these extreme outcomes are likely, we should assume that the payment structure and levels of these various agreements will differ substantially from contract to contract. The complexity of contracting will reflect the fact that *all* types of interconnections are in fact a function of the strategic use (their demand) of these settlement mechanisms by the ASes to meet their needs. For example, some ASes sell transit in a strategic manner (even below cost) so as to manipulate their own peering ratios. The next section explores some of the circumstances that shape the bargaining over interconnection.

# 5 Frictions in Settlement-Free Peering Bargaining

In our characterization of the early days of the Internet, the major distinction among ISPs was size. Two ISPs of a given size were likely to be fairly similar, and to have symmetric inbound and outbound traffic. As we noted above, in today's Internet, in addition to size differences, there are also differences in type associated with the direction of traffic flows. To highlight these differences, consider the relative incentives to engage in settlement-free peering by the following types of networks -- content (C), eyeball (E), and mixed (M) – that may also be characterized as large (L) or small (S). Figure 1 provides a schematic summary of the incentives we have already articulated above. In reality, most networks are a combination of content and eyeball ASes,[21]

[21] For instance, a Tier 1 network has a mix of eyeball and content ASes (all within a 2:1 ratio of all other Tier One networks to stay within their peering agreements).

however in the diagram below we focus on the following "pure-play" networks in the type-size space to highlight the differences in peering incentives:

- Large Eyeball (LE): large, mostly incoming traffic
- Large Content (LC): large, mostly outgoing traffic
- Small Eyeball (SE): small, mostly incoming traffic
- Small Content (SC): small, mostly outgoing traffic

Whether a network has a net "Willingness to Peer" (WTP) is represented by directed links in the graph where the node at the start of the directed link is taken to accept or deny a peering request from the network at the end of the link. Solid and dashed lines represent a positive ('yes') and negative WTP ('no') respectively.

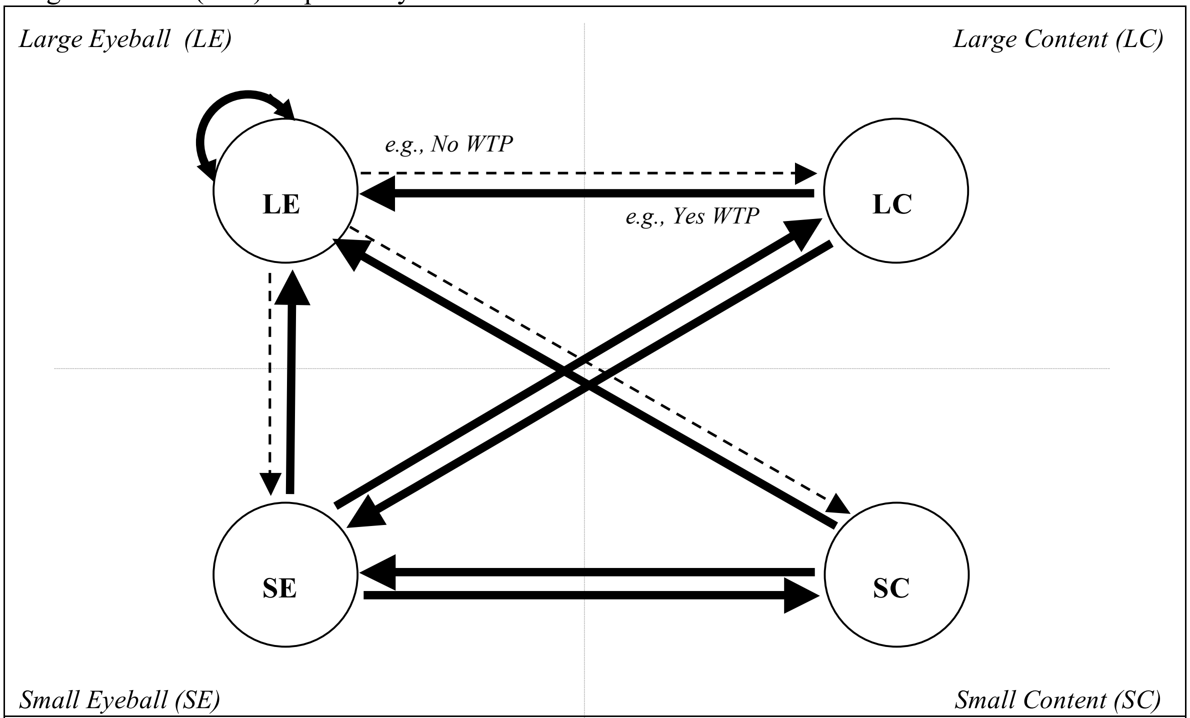


**Figure 1: Willingness to Peer (WTP) Incentives**

The diagram highlights that the LEs are unwilling to peer with all other networks save other LEs. This results because the LEs believe they have bargaining power over content providers, large and small, under the assumption that eyeball customers are less vulnerable to switching to another access provider than are content ASes. Also, since LE customers typically do not pay usage-sensitive retail rates, but instead pay via a flat monthly fee, the LE has little incentive to offer improved quality of service that might result from directly peering with a content network. LE will not peer with SE, because the size differential implies a customer / provider relationship, not peering. LE will peer with LE to handle the significant peer-to-peer (P2P) traffic, and since there bargaining positions are more nearly symmetric.

In contrast, LC ASes have a much more open peering policy, peering with any eyeball network, large or small. LC needs to send its bits to eyeball networks and performance matters, as the customers do pay usage-sensitive retail rates, typically being billed on the basis of volume. LC has no incentive to peer with SC, or vice versa, since little traffic will be traded. Finally, small networks, both content and eyeball, peer with any network where there is traffic to trade because peering reduces usage-sensitive transit costs and increases performance (because traffic has to follow fewer number of hops, reducing latencies).

In the next section we demonstrate additional complexities that introduce further strategic effects into the peering interconnection bargaining game.

# 6 Further Complexity of Settlement-Free Bargaining Strategies

The emergence of the heterogeneous ISPs—content and eyeball—implies that different sorts of actors have different sorts of bargaining power. A content provider, if it can control where its traffic can enter the network (e.g. if it is highly multi-homed) can influence the cost structure of other ISPs based on which of them end up carrying its traffic. It can use the power to control its forwarding as part of negotiating its interconnection agreements. Residential broadband providers are owning more and more of the "consumer eyeballs", and those consumers are a valuable asset, since the major content providers need to reach them. ISPs with a significant number of "eyeballs" can attempt to use access as a basis to negotiate favorable interconnection terms.

In the following subsections, we describe additional real-world negotiation strategies employed by ASes seeking to establish and maintain settlement-free peering in today's more complex and heterogeneous world.[22]

## 6.1 Refusal to peer

Uncertainties over how to allocate (shared or standalone) costs, especially across multiple ASes (when multi-homed) involving different contracts, may raise the risks of peering bargaining failures. Many large networks (and some small networks) will not accept peering requests from smaller networks, even if there are likely to be cost or performance benefits for the larger network. Some of the reasons that networks may cite for refusing to peer include the following:

- **Do Not Peer with Current Customers**: Almost no network will peer with its own customers, because doing so means loss of revenues from selling transit. This also means networks will not request transit from existing peers for fear of losing their peering.
- **Do Not Peer with Potential Customers**: Many networks also choose not to peer with anyone they see as a potential customer, under the assumption that potential customers will not buy transit from networks with whom they peer. However, there are potential peers who will not or even cannot buy transit from the provider. Even though these potential peers represent possible cost savings, increased scalability, lower latency, and all the other things peering brings to the table, most providers will not connect if the potential peer falls below certain requirements despite the potential benefit. So while these first two rules seem to make sense, their inflexible imposition may cost both sides valuable opportunities. This is a practical example that illustrates the impact of transaction cost and asymmetric information.
- **Do Not Peer with Existing Peer's Customers**: For large networks that already have diverse, robust peering, many peering requests come from customers of existing peers. Providers often turn down these requests. First, while stealing transit customers from one another based on price or performance is normal business practice, stealing a revenue generating customer by agreeing to a non-revenue generating relationship is considered very poor manners. The other ISP may reach out to the first network's downstream customers asking for peering in a tit-for-tat exercise. Second, agreeing to such peering

[22] This paper is based, in part, on the real-world experience of some of its authors and the stories they have gathered. Citations to actual interconnection agreements are not possible since these are typically regarded as confidential and proprietary information.

requests will move traffic off the original peering link, onto a direct link with customer network. This will change traffic ratios and volumes with the original peer, perhaps putting the larger peering relationship in danger.

- **Inflexibility, or Adherence to Peering Policy:** When large networks create a peering policy, they may strictly conform to it, to avoid the risk of being sued. The threat of lawsuits is valid, and possible concern about anti-trust scrutiny may apply to a few large networks. However, it is very hard to write in advance a policy that is detailed and complex enough to cover all the issues that may arise, so formal policies often preclude mutually beneficial negotiations.
- **Cost Sharing**: A provider will often not peer with anyone who has not demonstrated equal investment in infrastructure, resources, etc. The logic behind this includes:
  - Ensuring the peer has the ability to carry the traffic
  - Ensuring the peer is capable of troubleshooting problems
  - Ensuring the peer has the same investment in the quality of traffic

  These sorts of considerations can be seen as a further attempt to restrict peering to partners who are "just like me", making it is easier to defend the proposition that the peering has not relatively advantaged one party. Again, these sorts of rules may preclude some specialized cases of beneficial peering.
- **Perception**: In the real world of bargaining, some motivations are purely subjective. Network engineers almost always have a large amount of pride in their creation. They feel the networks they created are large, important, and significant on a global scale. A peering request from a network they feel is much smaller or less important may seem to diminish their own importance. Peering with the smaller network might diminish their network in the eyes of their colleagues. Decisions based on these subjective (and perhaps unrecognized) motivations, especially by engineers who are not aware or motivated by the economic drivers of the business, may cost the network dearly, both in hard-dollar costs, and in performance, scalability, etc.

## 6.2 Creating Incentives to Peer

Networks who would like to peer are frequently turned down for a variety of reasons, including those in the previous section. The long-term benefits of peering (e.g., cost savings, performance enhancements, and scalability) drive many networks to take unintuitive or even harmful (in the short term) steps in order to induce potential partners to peer. Some of these strategies include:

- **Force Traffic Over (Expensive) Transit:** Because of the reasons mentioned above, providers will frequently turn down peering requests from networks who are customers of existing peers. An obvious response for that customer, if they can control the routing of their traffic, is to cause their traffic to/from the prospective peer over the peer's transit connection. This response only works when the provider in question is not a Tier1 network, since Tier1 networks have no transit. But if the ISP has a transit path, forcing the traffic over that path will increase costs. The basic premise here is to raise costs of the provider until it agrees to peer. This response is, again, a game of "chicken", since it may raise the cost for both parties.
- **Lower Performance**: If a provider refuses to peer, a network may direct traffic to a smaller link, or not upgrade an existing one. If the link reaches capacity, it will precipitate congestion, which means packet loss, high latency, and performance degradation. Similarly, the network may direct traffic through trans-oceanic lines (e.g.

From London to Paris through New York), which increases latency and lowers throughput. Again, the basic idea is to raise the costs until the prospective peer agrees. And, as before, this strategy raises both agents' costs.

- **Move Traffic Away:** Most large networks do not have the majority of traffic source from or terminated on their own AS, but on the prefixes of their transit customers. Customer prefixes are often not single-homed, and hence there is more than one path to the customer. Say Network A asks to peer with Network Z, and Z denies the request. A may find some large customer of Z, C, to which A is sending a large amount of traffic through Z. It may be possible for A to find a second path to C. This other path may involve directly peering with the C, finding another transit path, or peering with a second transit provider of C. A special case of this strategy is called "donut peering". This is where a provider will intentionally seek out and peer with all of a network's downstream customers or their second transit provider, removing the incentive to peer with the network itself, and potentially harming Z through loss of revenue.
- **Cross Geographic Boundaries:** Although most large networks will not peer with small or medium sized networks, a smaller network which makes a large investment, such as crossing an ocean to meet the larger network may get an exemption to the Peering Policy of the larger network.
- **Interesting Prefixes:** If a network has something on its network that is interesting the potential peer, this can shift the bargaining. For example, a network with a Root Name Server will increase its chance of peering.

## 6.3 Strategies to Remain in Policy

This section reviews four strategies whose goal is to maintain the implemented settlement-free peering mechanism.

- **Traffic Engineering:** The term "traffic engineering" refers to the collection of management decisions an ISP makes, including the local configuration of the way BGP works, to allocate traffic to the different paths they control. In general, traffic engineering has a number of objectives, including keeping the load on various links in balance, and avoiding congestion of a single link. Traffic engineering techniques can also be used to keep peering traffic ratios within balance. For example, if ISP A has a peering relationship with ISP B, and A is sending too much traffic (out of balance) to B, A might arrange to send some its traffic to B via some transit path into B. This strategy serves to keep the peering ratios in balance (as B demanded), but actually increases the cost to B, since there is now more load on its transit service. This sort of traffic engineering is commonplace in the Internet today, as operators try to optimize their own costs while conforming to the various terms imposed on them in their various interconnection agreements.
- **Buy Additional Services**: Most network providers do not supply just full transit but instead have a whole portfolio of products for sale, such as raw fiber or derived fiber links, and collocation. If a network finds itself violating the peering policy of a large peer and is unable to rectify the situation, it may be able to purchase other services in order to preserve (or facilitate) the peering relationship.
- **Incentives to Customers**: As was mentioned in the partial transit section, some networks will offer incentives (low price or even free transit) to customers who will help correct a policy violation. It is very common for large content network to charge different prices to customers who have eyeballs than customers who have content.

- **Threat of Disconnection**: If the only path to a network is over the peering links, then shutting down peering will cause disconnection between the two networks. If either network has full transit, it will require the assistance of a 3rd party network. But if configured properly, this gives a very large incentive for a peer to continue peering.

# 7 Bilateral Negotiations, Market-Failure and Entry of CDNs

We have discussed how the range of interconnection agreements have expanded and some of the reasons for such expansion. However, even with a wider array of potential agreements to choose from results in efficient bilateral negotiations, such negotiations may still result in problems in end-to-end provisioning.

Recall that end-to-end value-flows in the Internet can be highly complex and heterogeneous, involving not only traffic volume and destination addresses but also internalization and transfers of application and end-host dependent values. Traffic volumes and access to prefixes may be provisioned *locally* in a pair-wise manner but transfer and internalization of other value flows in a distributed system often involves coordination of many self-interested ASes. Our collective experience with trying to move from the legacy single-class of service Internet toward an Internet that implements standardized approaches for delivering end-to-end quality of service (QoS) and multicast in the general Internet and across virtual private networks (VPNs) demonstrates the challenges of coordinating a set of self-interested stakeholders. The system of bilateral negotiations using a simple set of standardized contracts that resulted was partially a response to the challenges of full multilateral coordination. The scalability and stability of end-to-end interconnections in the Internet has been dependent on the stability of the underlying bargaining mechanism that implements only a restricted set of transfers. However, the collective price paid for the limitations inherent in building an end-to-end Internet from a collection of bilateral bargains has been the lack of services (QoS, multicast) that might arguably benefit all.

As noted earlier, large content providers, and at times content consumers, may be presumed to have a high willingness to pay for better than Internet's best-effort packet transport services, However, incumbent ISPs have consistently failed to coordinate and service this end-to-end demand. This market failure helped provide entry incentives for third party content distribution overlay networks (see [CLA05,HOF05]) to implement and internalize marginal value-flows. Entry and scaling by such an overlay network enabled new markets, interestingly using the same bilateral contracts. It achieved this through simultaneously lowering the transaction costs to end-hosts (because content providers did not have to negotiate with multiple ASes for content collocation) and using the underlying Internet interconnection bargaining mechanisms to interconnect to the various providers of transport services. Overlay Content Distribution Networks (CDNs) in effect transform the single principal (the end-host content provider) multiple agent (packet transport ASes) coordination problem into a single-principal (e.g. the content provider), single agent (the CDN) who in turn becomes the single principal interacting with multiple agents (packet transport ASes). A CDN as a principal internalizes the (provisioning, monitoring and enforcing) transaction costs of bargaining with the transport ASes, but benefits from strong economies of scope and scale.

The interested reader is referred to [FAR06,FAR07] for a more in-depth discussion of entry and scaling of CDNs and how asymmetric and indirect externalities, which are features of this markets, described within Two-Sided Markets framework [ROC05,ARM05] can be used strategically in the bargaining games to overcome market-failures given limitations in current value transfer mechanisms.

## 8 Conclusions and Future Work

The Internet is a network of networks, comprised of entities called Autonomous Systems (ASes) that, as their name implies, are semi-autonomous administrative domains managed, in many cases, by commercial entities known as ISPs that compete with each other both directly and indirectly. How these ASes are interconnected influences how traffic (packets) is routed across the Internet, the reachability of content, and the services that can be supported. In addition to helping to determine the physical routing of packets, the business agreements by which ASes are interconnected also serve to route value transfers (money) between and among ASes.

Historically, there were two principal types of interconnection agreements: settlement-free peering and transit. Without too much damage to reality, interconnection could be described by a hierarchical model in which smaller ISPs purchased transit from large ISPs and the largest ISPs exchanged traffic at multilateral (public) or, more commonly, bilateral (private) peering points. Smaller ISPs, if they saw mutual benefit, could also arrange peering agreements. Under the assumption of approximately symmetric traffic and costs, it made sense for similar ISPs to exchange traffic without any monetary payments. Using only these two types of standardized agreements, the Internet was able to scale and grow substantially in geographic scope, traffic volume, and capabilities. It also grew in terms of economic activity both directly focused on the Internet and indirectly dependent on the Internet's health and continued growth.

The fact that the Internet has been able to scale as a network of competing yet cooperating networks, resulting in a relatively stable and robust set of interconnections, is perhaps remarkable. Of particular note is that this has happened in a mostly un-regulated market – in rather dramatic contrast to the legacy of regulation that has characterized interconnection in the PSTN. With the growing importance of the Internet, including its role as a replacement for the PSTN, it is inevitable that various parties will question whether the contracts and mechanisms that have sustained interconnection in the Internet to date will be sufficient to sustain stable interconnection in the future, and whether the "hands off" regulatory approach remains the right approach. These complex and difficult questions are beyond the scope of this paper; our goal is a simpler one, to provide some factual information about Internet interconnection today. Debate about policy needs to be informed by a realistic understanding of what is actually happening today, in the increasingly complex and distributed system of bi-lateral contracts that transfers costs and benefits across pairs of interconnecting (and increasingly multi-homed) ASes.

The goal of this paper is to provide a richer view of what real-world Internet interconnection looks like, relying in part on contributions from industry practitioners with deep knowledge of what negotiating interconnection looks like on the ground, from engineers engaged in designing the technologies that support interconnection, and industry analysts/economists concerned with the business and policy implications. We conclude that the simplistic characterization of interconnection as either settlement-free peering or transit agreements does not adequately capture the dynamic nature of what is currently being negotiated. With the growth of the Internet the diversity of ASes has expanded and the presumption of symmetry has eroded. New types of providers such as content-heavy ISPs such as Abovenet and Cogent and large content providers like Google, Yahoo, and YouTube are interacting with ever-larger eye-ball heavy ISPs like Comcast and Verizon. New types of players like Akamai and Limelight are providing overlay services. These new types of providers lead to traffic patterns that are highly asymmetric, as traffic flows from content to eyeball, and also lead to changing perceptions regarding the symmetry of value flows. In response to this growth and resultant changes in the Internet industry landscape, the range of interconnection contracts have expanded to include paid peering and partial transit, reflecting a filling in of the contracting space. By understanding the preferences of ASes of different size and type for different sorts of interconnection arrangements and by understanding more fully the range of strategies employed by ASes to achieve their preferred modes of interconnection, it is possible to gain a more complete understanding of how interconnection has changed and is likely to change in the future.

Our view is that the earlier world of settlement-free peering and paid full transit agreements was an appropriate, market-based response to the earlier world of the Internet. In this context, one can interpret the emerging paid-peering and partial transit types of agreements, as well as many of the seemingly strange strategies employed by different ISPs in their efforts to negotiate and manage their interconnection agreements, as consistent with on-going robust competition in the market place. What it also suggests is that the landscape of interconnection is getting increasingly complex. Unfortunately, due to the private nature of these contracts we can only hypothesize that this expansion of the bargaining set is *partially* due to entry by the content ASes, and infer that the emergence of the newer contract types yields mutually self-enforcing efficiencies since such mechanisms are available to all ASes.

We do not attempt to draw any policy conclusions from our evidence. Indeed, even our attempts to catalog a list of possible implications reveals areas where the various authors disagree. We are prepared to say that while some of the bargaining may have been perceived as unfair, there is little evidence, aside from a few highly visible events such as de-peering actions, that the range of negotiated contracts, whether discriminatory or not, has harmed the overall connectivity of the Internet. Most users very seldom encounter an event where a failure to negotiate an interconnection agreement (as opposed to a failure of a link or a router) keeps them from reaching some part of the network. If there is a failure today, it will be found not in a lack of reachability, but in the failure of certain sorts of providers and services to emerge in the market, potentially due in part to the lack of appropriate mechanisms to manage value flows. Further, as the CDN example demonstrated, under some circumstances such failures can be corrected by third party entrants with incentives to internalize potential value-flows from indirect externalities. The discovery of additional hypothetical failures would require more work than we have been able to undertake. However, it is worth considering the possibility that different sorts of value flows (e.g. from the advertiser toward the consumer) might help to increase the penetration of consumer uptake of broadband by reducing the cost of broadband access. Advertising subsidizes the media industry, so it is not intrinsically inappropriate to ask whether such an outcome could also happen in the Internet.

We also have a cautionary conclusion: if one should be motivated (for whatever reason) to contemplate some regulatory rule to manage interconnection (which the debate over Net Neutrality is, in part, about [LEH07]), the design of such a rule will be both complex and informationally demanding.[23] Any simplistic rules that try to define network neutrality as the

[23] Laffont and Tirole present a distinction about complexity and information tradeoffs [LAF93]. They state that (at page 8):

> *Complexity more vaguely refers to the degree of mathematical sophistication or subtlety of the rule. 'Choose prices so as to equate revenue and cost over some regulatory period' or 'charge marginal cost for each period' is not a complex rule, yet either one is informationally demanding…. an optimal regulatory rule is likely to use pieces of information about technology and demand held by the regulator. There is nothing wrong with the use of an informationally demanding rule. The economist can instruct the regulator to offer the firm the optimal regulatory scheme conditional on the regulator's information. But, unlike a simple rule, an informationally demanding rule is not always robust to the perversion of regulatory behavior. The agency may not exert enough effort to collect information about the industry, and it may use its information strategically to reach its own goals or to collude with the industry or other interest groups.*

elimination of discrimination will fail even to match today's reality by a wide margin. There is a substantial level of economic discrimination today just in the variation in willing to peer, and the emergence of paid peering and partial transit only increase this space. Partial transit and paid peering may be seen as efficiency-enhancing responses to changing market conditions. While there may be opportunities for abuse by providers with excessive bargaining power, the complexity of what is in place today, and what seems to be working today, would argue that the best way to address any potential concern would be to focus on the sources of bargaining power and identify anti-competitive opportunism, rather than to impose *ex ante* restrictions on the range of bilateral contracts.

Other actions, both by industry and academia, could be contemplated going forward. For example, it is clear that the commonly understood, "old-fashioned" model of peering and transit reduced bargaining costs, which is also efficiency-enhancing. If it were possible to bring a "best practice" or "common practice" in interconnection out from the non-disclosure agreement and into the light, this might also help reduce bargaining costs, but in a more flexible way than might be achieved via regulatory constraints. An industry forum that tried to discuss this openly (and which was given a clear mandate for how to behave so as to avoid anti-trust concerns) might offer a substantial contribution to efficient operation of this asymmetric world, and might mitigate the sorts of fears that have prompted calls for more direct regulation. Neutral development of cost models and hypothetical value flow might inform such a forum. Lack of real data and available cost models hinder any academic contribution to the efficiency of this process.

For the future, the growth of multimedia traffic, including delay-intolerant applications such as voice-over-IP (VoIP), will imply a growing need for differentiated quality of service (QoS) to accommodate the requirements of different types of traffic. The lack of QoS support in the legacy "best efforts" Internet has quite possibly hindered the emergence of some applications that demand enhanced services, and the ability to cache content enabled innovation in content distribution and facilitated the rise of Content Distribution Networks. We can speculate that there may be new sorts of applications that cannot be supported using CDNs or built by exploiting application-level interconnection with other kinds of networks such as the PSTN. In order for such applications to emerge, the community of ASes will need to coordinate and provision better end-to-end services. Tier 1ASes have begun to implement interprovider QoS over peering links to support VoIP. Interconnections are also emerging for interprovider VPNs, developments that may signal the need for more efficient coordination and contracting mechanisms by ASes, perhaps as packet-transport continues to become a commodity market.

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# 10 Appendix-- Practical Aspects of Interconnection

Interconnection between two ASes is done by physically connecting the routers of one AS to the routers of another AS. This may be accomplished over a long distance if the routers are geographically dispersed using high capacity transmission links or over a short distance if the routers are located in the same building (e.g., a so-called "carrier hotel"). These interconnections may be public or private.

## 10.1 Public interconnection

Public interconnection, sometimes called just public peering because public interconnects are almost always peering, is via some sort of shared switching technology that allows each peering partner to make one physical connection to the switch and gain a potential connection to all the other peering partners. The switching technology can be any shared network fabric, such as ATM or Frame Relay, but is usually an ethernet switch. Multiple networks connect to the shared switch, and then are free to negotiate the terms under which they exchange traffic. The advantage to public interconnection is a network need only have a single physical connection, requiring only a single router port in order to interconnect with many other networks. Also, networks tend to aggregate where there are shared switch fabrics, removing some of the geographical constraints.

The disadvantage is the network only has a single router port for multiple peering sessions. This can cause congestion problems because the router port is a shared resource, and each network has no way of knowing what traffic from other networks is destined for their peer's port.[24] Another disadvantage is a network has to extend its infrastructure to the location of the shared fabric. Generally, the quality of service delivered via multilateral peering exchange points has suffered because the networks lack adequate incentives to support the actual level of traffic since it may not be clear who is to blame for poor end-to-end service when the traffic passes through a multilateral peering point.

## 10.2 Private Interconnection

In contrast, in private interconnection, a link is dedicated between the two networks. This gives the two networks much better control over their bilateral interconnection and makes it easier to ensure adequate quality of service (congestion control) and to identify which network is at fault when traffic is exchanged bilaterally. On the other hand, the disadvantage is that the costs of the link are not shared across interconnections with multiple networks.

## 10.3 Economic costs of Interconnection

There are a number of costs that are associated with setting up and maintaining an interconnection agreement and these differ depending on whether it is a peering or transit agreement. Since these settlement agreements are, in part, a mechanism for allocating the costs of

[24] For instance, assume Network Z has a gigabit ethernet port on a public switch fabric. If both Network A and Network B peer with Z, and both A and B try to send more than 500 Mbps each to Z, congestion will occur. However, there is no way for A and B to know what the other is sending, so there is no way to avoid the packet loss except trusting Z to maintain its infrastructure properly.

supporting E2E packet transport across multiple networks, it is worthwhile considering how the different types of contracts impact costs. The costs for networks to interconnect with other networks are varied, but can be roughly decomposed into two main components, *ex-ante setup* and *ex-post operation* costs [NOR02]. For simplicity, we will take the example of a network connecting to a public peering fabric when considering peering, and the example of full transit when considering transit.

The set-up costs include both the capital costs of the requisite equipment, as well as the transaction costs associated with negotiating the agreement.

### 10.3.1 Set-up capital costs

For peering, the capital costs are well defined and market driven. They vary by geography and volume, but are well understood and easy to compute prior to attempting interconnection. They include: i) Rack space at the peering point (to house the equipment of the networks), ii) Switch port, iii) Backhaul (the connection from the rest of the network and the switch location) and iv) Infrastructure hardware (routers, switches, etc.). These costs are all necessary under the assumption that the network in question has no prior infrastructure at the public peering point. These costs are usually a fixed, and relative to the size of the network involved. A small network can collocate a small router taking up just a few rack units, connect to the public switch fabric with a 100 Mbps port, and have a small leased line to backhaul traffic to the core of their network. A very large network may need an entire rack or more to support the necessary hardware, require multiple 10 Gbps ports on the switch fabric, and a similarly large amount of backhaul.

For transit (under the assumption of private interconnection), typically the only technological cost to consider is the interconnection link, and a router port on each network. This differs from peering because the full transit customer does not require any infrastructure outside the core of its network. Purchasing full transit frequently requires long-haul capacity to reach the transit provider's network. However, no co-location or additional infrastructure is required, whereas peering at a public peering oint requires the long-haul capacity as well as colocation at the peering point and a router.

An exception to this arrangement arises when the transit customer has few or expensive choices for transit providers in their current locations, in which case the transit customer may extend its network to a location with more providers, giving them choice and usually lower prices. The cost of the extension will include router(s) and rack space, just as in peering. There would also be an additional cost for the backhaul depending on the location chosen. The most common location to choose is the closest peering point. Peering points aggregate large numbers of networks, so there is downward price pressure for transit interconnections that are implemented at a public switching point. (If two networks agree to a transit connection at a public peering point, they would not normally connect via the switch, but by means of a direct connection between their two routers.) And extending to the peering point allows the network to engage in peering for just the cost of the switch port. This added benefit can swing the decision to extend the network as well.

### 10.3.2 Set up transaction costs

The transaction costs are harder to quantify because they include many search, agency and provisioning costs. For a peering agreement, they include: i) Time to find, contact, and negotiate with a potential peer; ii) Configuration of network to support the potential peer's peering policy[25]; iii) Engineering resource to support additional network complexity involved in peering vs. simple transit relationships; and, iv) Administrative overhead to deal with at least one additional and perhaps multiple external vendor relationships. These costs are highly variable. Contacting a network with an open peering policy might be easy - in fact, they might contact you, removing nearly all the search cost. Contacting and negotiating with a large potential peer who has a restrictive peering policy may be difficult. Sometimes it is not even possible to find the right person in the organization to start the negotiations.

The transaction costs associated with transit agreements are typically much lower because the network selling transit is interested in attracting customers and the customer service provided is one of the benefits that justifies paying more to terminate traffic.

### 10.3.3 Operating Costs

Operational costs for peering are varied, mostly because peering is not homogeneous. A network will peer with multiple other networks, and each peer will have a different operational cost. Operation costs include dealing with degraded or down links. These costs vary dramatically because peers are varied. When the connection to a peer is down or degraded, the peer might not have a large incentive to troubleshoot the problem because there is no monetary motive. This can cause a drain on the other side of the peering relationship if resources are spent trying to contact the unresponsive peer, tickets are left open, time is spent troubleshooting the problem without help from the other side, etc. The same problems exist when a link needs to be upgraded. If one peer does not have the capital budget or engineering resources, or even just the internal motivation, a link may become saturated and cause performance issues. This will cost the other peer significant time and money to work around the problem through engineering effort, expenditures on additional transit, or other means.

The basic issue is that the operational costs for peering are supposed to be symmetric, but peers rarely both dedicate the same resources to the relationship. This discrepancy cannot always be balanced by one peer putting in more resources. For instance, if a link goes down due to configuration error, the network which made the error must correct it; the other network cannot fix the problem on its own no matter how much effort is expended.

In contrast, because transit is a paid-for service, the transit provider absorbs some of the operational costs. This means operation costs for transit are asymmetrical, in the favor of the network purchasing transit. For instance, transit contracts typically include Service Level Agreements (SLAs) that have monetary damages for outages that are not repaired quickly. This means networks do not have to spend as much engineering time troubleshooting outages as with peering. And they have greater confidence the problem will be fixed in a timely manner, removing the possibility of extended problems that continue to absorb resources. Networks may prefer having the "teeth" of a customer-based contract over soft peering assurances that both ISPs will work diligently to fix peering-related issues.

Here we should note the operational cost for Partial Transit and Paid Peering can be significantly more than Full Transit, but are not as high as Settlement Free Peering. The differences are in engineering resources, and perhaps hardware. But both Paid Peering and Partial Transit are still

[25] The cost of reconfiguration is influenced by the technology in place in the two networks and by the requirements of the peering agreement. A network that already peers at one point, may find it less expensive to peer at a second point. A potential partner might require a network to peer on multiple continents.

paid-for services, so the costs are asymmetrical as the provider tries to internalize the customer's costs in order to increase business.

And all services (Full or Partial Transit, Paid or Settlement Free Peering) increase operational cost somewhat. Every time a network, any network, adds a link, it increases complexity, and therefore cost of operating the network. However, adding a single link to a large, complex network with thousands of existing links adds less cost than adding a link to a small network with only a few existing links. When a large, complex network adds a link, the operational expertise, infrastructure, and systems are already in place to handle an additional link. In a small company bringing up its first peering link, it is likely none of this support structure is in place. Even for a small company with a few peering links in place, it is far more likely the existing systems are either not scaled appropriately (e.g. there is only one engineer who understands peering), or there are no systems (e.g. the "peering database" is a spreadsheet on someone's laptop).

Table A1 summarizes the cost component that the settlement mechanisms transfer between ASes.

| **Cost** | | **Peering** | **Paid-Peering** | **Partial-Transit** | **Transit** |
|---|---|---|---|---|---|
| **Setup** | *Technological Cost (Nature)* | Fixed | Fixed | Fixed | Fixed |
| | *Technological Costs (Level)* | Low | Buyer: Low<br>Seller: High | Buyer: Low<br>Seller: High | Buyer: Low<br>Seller: High |
| | *Symmetry* | Symmetric | Asymmetric | Asymmetric | Asymmetric |
| | *Transaction Costs (Level)* | High | Buyer: High<br>Seller: High | Buyer: High<br>Seller: High | Buyer: Low<br>Seller: High |
| **Operational** | *Nature* | Variable | Variable | Variable | Variable |
| | *Technological Costs (Level)* | High | Buyer: Low<br>Seller: High | Buyer: Low<br>Seller: High | Buyer: Low<br>Seller: High |
| | *Symmetry* | Symmetric | Asymmetric | Asymmetric | Asymmetric |

**Table A1: Cost Structure of Contract Classes**