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An economic analysis of routing conflict and its resolution

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ABSTRACT

Thousands of competing autonomous systems (ASes) must cooperate with each other to provide global Internet connectivity. Each AS has independent economic objectives and retains autonomy in setting their routing policies independently to maximize its profit. However, such autonomy enables ASes to produce conflicting routing polices and thus raises route oscillations between them (i.e., routing divergence). This paper studies the basic problem of routing divergence by investigating real ISP pricing data. We first demonstrate that routing divergences occur under economic dependency cycles, i.e., provider–customer cycles, of different ASes which are raised by economic conflicts between themselves. We then propose a provable cycle-breaking routing mechanism to detect and solve economic conflicts and route divergence. We show that every cycle-breaking strategy allows ASes to maximize their own profits to converge to a Nash equilibrium with a profit-sharing mechanism derived from the coalition game concept of *Shapley value*. At the Nash equilibrium point, the cycle-breaking strategies maximize ASes' profits and encourage ASes so as to ensure divergence-free routing.

1. Introduction

Autonomous systems (ASes) connect with each other using the Border Gateway Protocol (BGP) [1]. They specify their local routing policies to select best routes to destinations independently. This allows ASes to exercise their own autonomy in route selection. In the meantime, routing policies need to be compatible with ASes' desired economic goals, such as cost reduction and revenue maximization. This creates an interesting scenario that ASes need to compete with each other but also collaborate with others so as to provide global connectivity.

While the route selection of an AS looks feasible locally for the purpose of revenue maximization, different ASes may set *inconsistent preferences* over multiple candidate paths to a destination. As a result, there may be conflicts of routing policies among different ASes, thereby creating routing divergence (or routing instability) [2]. Previous studies investigate routing divergence by modeling routing policies [2,3] or proposing mechanisms to resolve conflicts [2–4]. Such studies typically address routing divergence from a protocol design perspective. However, their proposals do not consider ASes' economic goals (i.e., profit maximization), which is the main reason of creating undesirable consequences of routing divergence [3]. Therefore, it is crucial for us to address routing divergence from an economic perspective.

Gao and Rexford [5] proposed important guidelines for routing policy configuration (also known as the *Gao–Rexford conditions*) to guarantee divergence-free routing, according to the static economic constraints (i.e., commercial relationships between ASes). These guidelines are simple and effective enough to prevent routing divergence [6]. On the other hand, the Gao–Rexford conditions may be too restrictive and cannot ensure ASes to maximize their profits. The conditions require links

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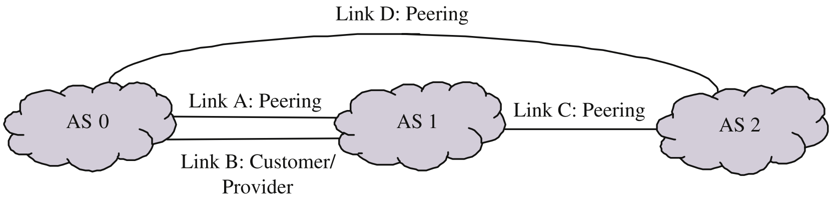

Fig. 1. An example that shows the complex business relationships among ASes. Suppose that AS 0 and AS 1 peer with each other via Link A in Asia, and AS 0 buys service from AS 1 via Link B in North America. Also, suppose that AS 1 peers with AS 2 via Link C in North America, and AS 0 peers with AS 2 via Link D in Asia. This arrangement among Link B, C, and D is precisely the peer-provider cycle which conflicts with the Gao and Rexford conditions (e.g., Guideline A [5]) [3]. This scenario mandates that AS 1 prefers the routes to all destinations in AS 2 via AS 0 over AS 2 though AS 1 has a better route to the destinations via Link C. Thus, AS 0 needs to pay for connectivity between AS 1 and AS 2. Actually, there are many similar real-world examples [3,7].

connecting ASes have only single transit agreements, either provider-to-customer agreements or peer-to-peer agreements. However, these links may carry multiple transit agreements in practice [7]. Moreover, the conditions may not allow ASes to maximize their profits under some network settings. Fig. 1 [3] shows a setting that is precisely the cycle that is prohibited by the Gao–Rexford conditions, which limits ASes from maximizing their profits [3], even though the conditions ensure routing convergence. In the arrangement, Link A and Link B are two parallel links between AS 0 and AS 1 with different transit agreements, and AS 2 peers with AS 0 via Link D and peers with AS 1 via Link C [3]. Liao et al. [7] relaxed the conditions to address this issue and ensure routing convergence even when peering is carried out using multiple transit agreements. They require ASes having AS relationships beyond the immediate neighbors when configuring routing policies. However, it may not be easy for network operators to obey these static guidelines because they have limited knowledge about AS relationships that are always evolving [3,8]. *Normally, routing policies are configured according to AS relationships* [5]. *However, routing policy changes may cause inconsistent view of AS relationships between different ASes at any time, which result in conflicts of routing policies.* Thus, it is vital to design a mechanism to dynamically break routing conflicts while allowing ASes to maximize their profits.

In this paper, we examine the route divergence problem in ASes[1] that arise from economic conflicts. We argue that if ASes set routing policies based on their own *economic incentives*, then they may set conflicting routing policies, leading to routing divergence, which stops these ASes from achieving their economic goal. This paper aims to ensure divergence-free routing while allowing ASes to achieve their goal, i.e., profit maximization. To achieve this, we need to address the following challenges: (i) how to dynamically detect economic conflicts in routing and identify which ASes raise such conflicts during route selections? Although existing routing stability schemes tried to detect and prevent routing conflicts, they failed to clearly identify which ASes play key roles in routing conflicts, which is an important step to allow ASes to maximize their profits. (ii) how to distributively break the conflicts during route selections while allowing the ASes to achieve their economic goal? The objective of the paper is to answer these questions by exploring the relationship between Internet economics and Internet routing divergence.

In response to these challenges, we propose a runtime mechanism to guarantee divergence-free routing and at the same time, profit maximization between ASes. The runtime mechanism dynamically infers the provider–customer relationships between ASes by examining the route change patterns during routing selections, and breaks the provider–customer cycles to achieve divergence-free routing while allowing ASes to achieve more profits in a distributed manner. Specifically, we have three main contributions.

- We study real ISP pricing data and provide economic justification as to why ASes produce conflicting route selection policies. In the economic context, these conflicting policies are set by ASes due to their economic goals to maximize their profits.
- We prove that the routing system is divergence-free if there does not exist provider–customer cycles under our economic framework. We develop a runtime cycle-breaking routing mechanism to guarantee divergence-free routing and allow ASes to achieve more profits, which is distributively performed in the ASes.
- We leverage the Shapley value mechanism [9] to ensure fairness in cycle-break routing. In particular, we prove that our cycle-breaking routing strategies allow ASes to maximize their profits, and the resulting solutions are indeed the Nash equilibrium.

The rest of the paper is organized as follows. In Section 2, we briefly review the basic problem of routing divergence and roles of ASes in Internet routing. We model the economic incentives of ASes in routing divergence in the Internet in Section 3. In Section 4, we propose a proved cycle-breaking mechanism to solve the routing divergence issue. Section 5 implements the Shapley value mechanism to allow AS to maximize their profits. Sections 7 and 8 present the related work and conclude the paper, respectively.

[1] In this paper, we use "AS" and "vertex" interchangeably.