Traffic Engineering vs. Content Distribution

A Game-Theoretic Perspective

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Overview

- **Traffic Engineering** is the optimal assignment of **users** to **routes** in a network

- **Content Distribution** involves **users** selecting content from various **servers**

- These two may be in **conflict**!
  - The Traffic Engineer does not anticipate that users may change behavior in response to his decisions!

The Traffic Engineer

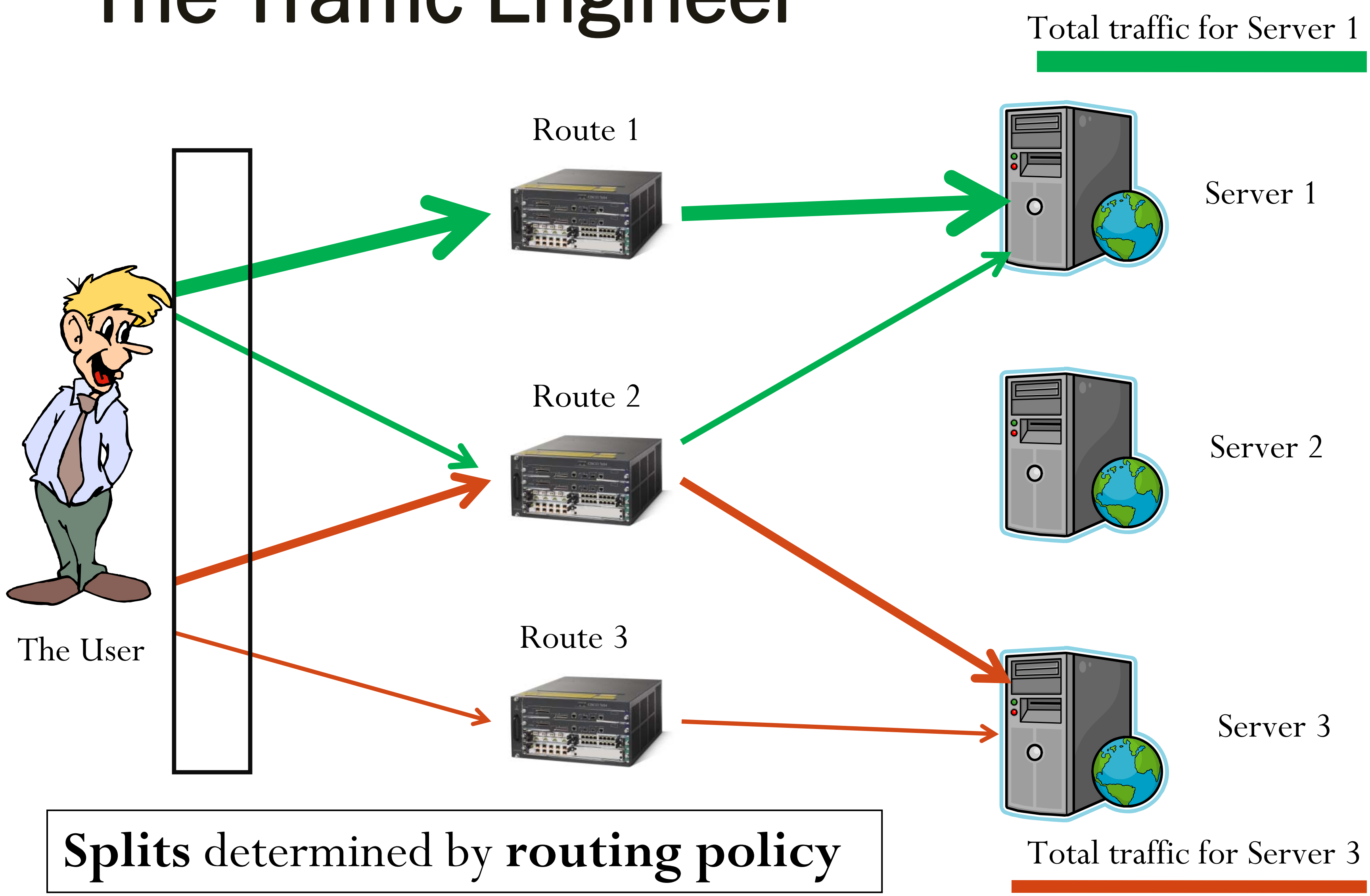
- Sees current traffic between **users** and **servers**
- Assigns **routes** to each **user-server** pair
  - **Routes** may involve overlapping **resources** (e.g. **links**)
  - Flows through **resources** generate **congestion**

- Given traffic $\vec{e}$ the engineer chooses a routing policy $\vec{\pi}$
  - He wants to minimize the total congestion at the resources:

$$\sum_{j \in J} L_j(f_j(\vec{e}, \vec{\pi}))$$

  - Flows: $$f_j(\vec{e}, \vec{\pi}) = \sum_{ms} \sum_{r: j \in r, r \in R_{ms}} \pi_{mrs} e_{ms}$$

The Traffic Engineer



The Users

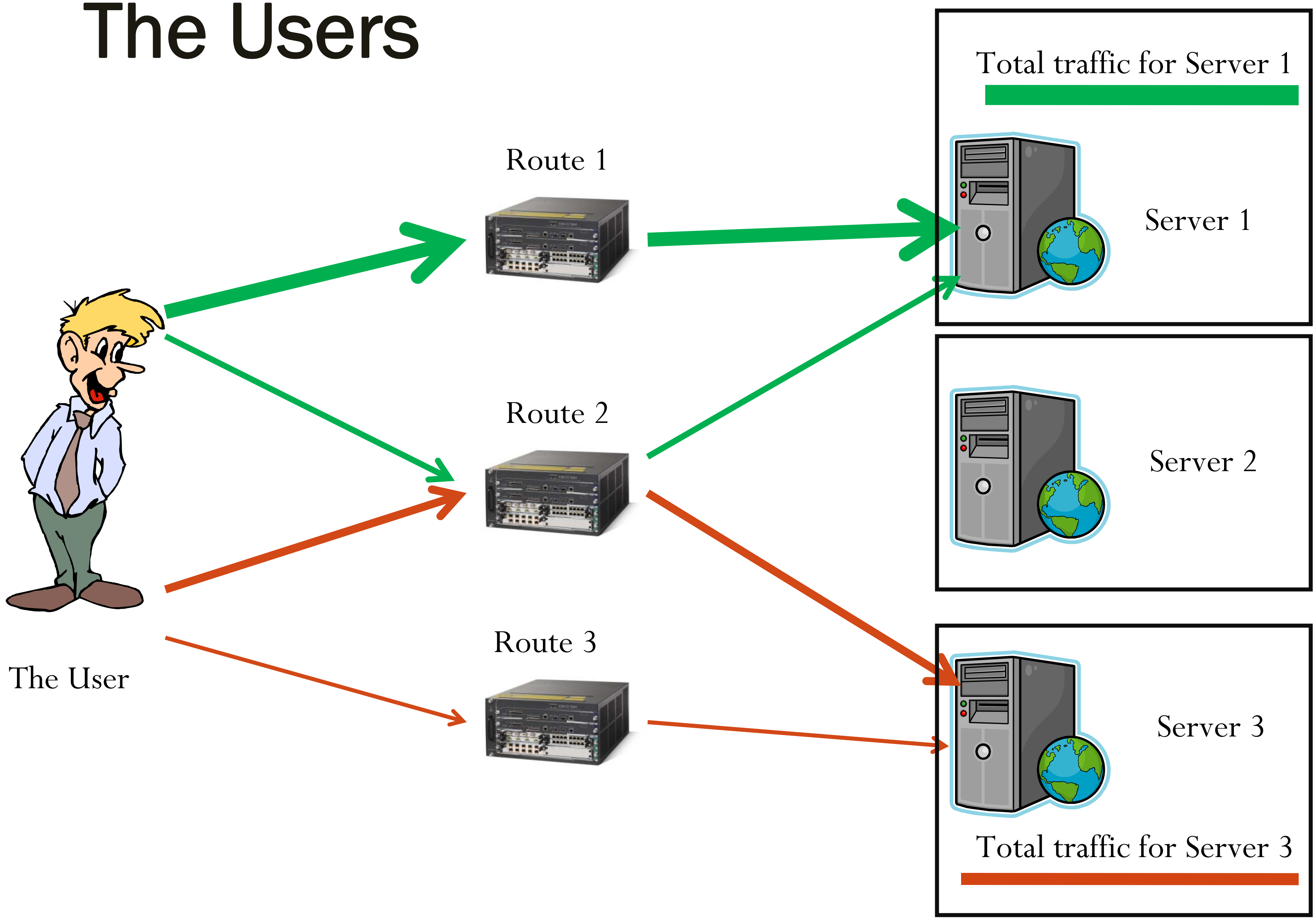
- See current **routing assignment**

- Choose how much traffic to request from each **server**

- Given routing policy $\vec{\pi}$ the users select servers and generate traffic $\vec{e}$
  - They want to minimize the **price** they pay to access servers

Users determine how much traffic to send to each **server**

The Users



Prices and Latency

- Users of distributed content often use **signals** when choosing servers
- Example of a signal: **delay** or **latency** to the server
- Abstraction: flow-dependent **price** $p_j(f_j)$ on each link j
  - Price may simply be the **delay** $l_j(f_j)$ of link j
  - Or some more complicated function:

$$p_j(f_j) = l_j(f_j) + f_j l_j'(f_j)$$

- Price of a **route** is the sum of prices of its links
- Price to a **server** is the average price of its routes, as determined by the Traffic Engineer's **routing policy**

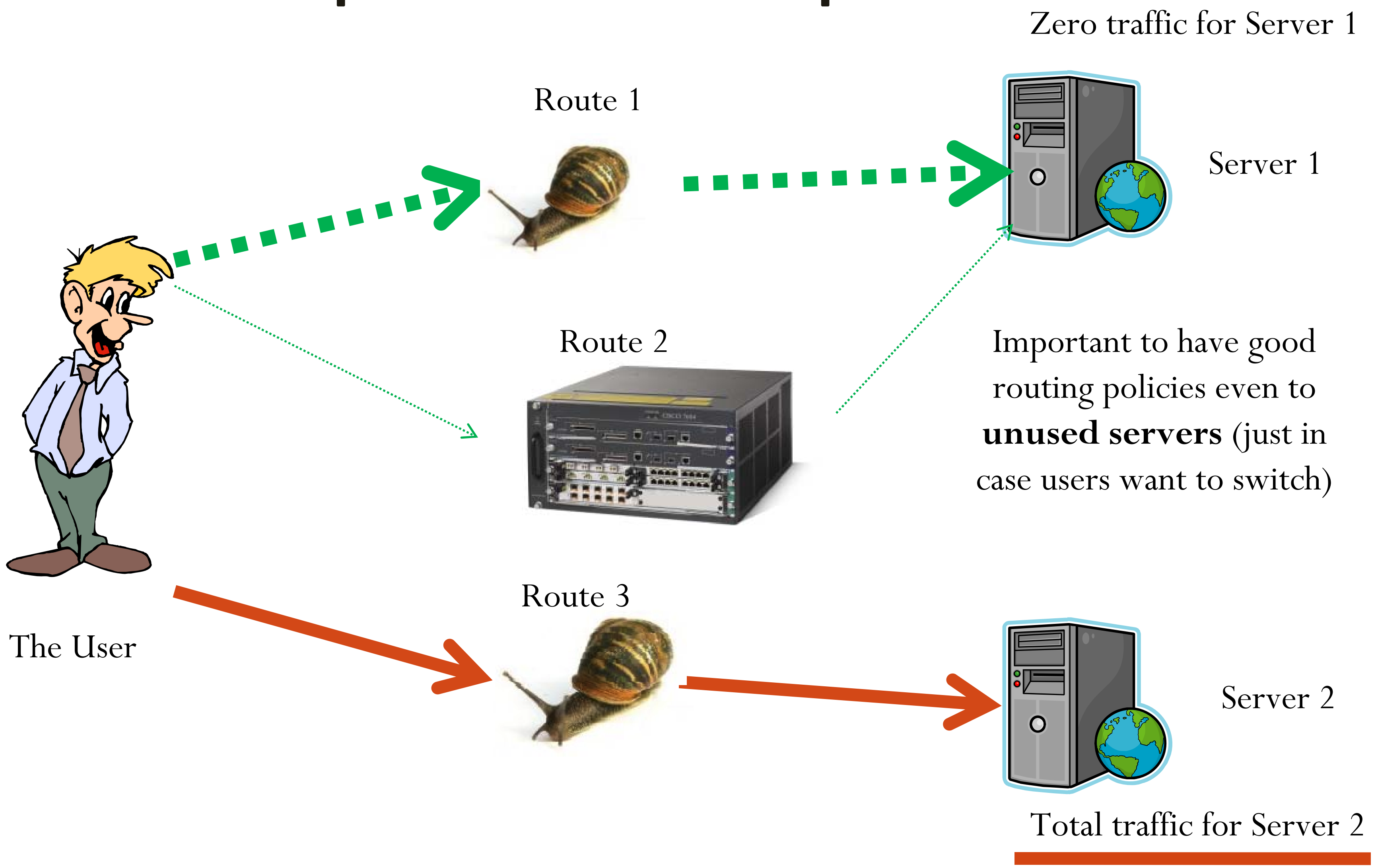
Prices and Wardrop Equilibria

- We assume users are **infinitesimal**
  - Individually, their decisions do not greatly impact the flows
- Collectively, in **equilibrium**, they only communicate with servers that have the minimum prices
- The resulting traffic implicitly minimizes an **objective function**:

$$\sum_j \int_0^{f_j} p_j(t)dt$$

  - This is the **implicit objective function** of the users

The Importance of Optimism



Important to have good routing policies even to **unused servers** (just in case users want to switch)

Pigovian Taxes

- Suppose the **delay** on a link is $l_j(f_j)$
- Then the **total delay** on that link is $f_j l_j(f_j)$

- Problem: Users do not account for the delay they impose on **others** through their decision!

- Solution: Charge them a **Pigovian tax**
  - Have them act as if delay (price) is $l_j(f_j) + f_j l_j'(f_j)$
  - The extra term forces them to **internalize** the effect they have on others

Unified Objectives

- When the Traffic Engineer's congestion function is **total delay**: $L_j(f_j) = f_j l_j(f_j)$
- And the Users' price function has a **Pigovian tax**:

$$p_j(f_j) = l_j(f_j) + f_j l_j'(f_j)$$

  - Then both parties have the **same objective function**
  - There is **only one equilibrium**, and it is the **best possible outcome** (i.e. total delay is minimized over all server choices and routing policies)

Dynamics

- Traffic Engineering is typically done on a **slow timescale**, e.g. a few times a day
- Users of distributed content may change their servers **very quickly**
  - So between changes by the Traffic Engineer, the users have time to converge to the **Wardrop Equilibrium**

- Under Unified Objectives, these dynamics converge to the **best possible outcome**
- With different objectives, the dynamics may be unstable and suboptimal

Extensions

- The results extend gracefully to:
  - Multiple classes of users
  - Multiple types of content
  - General overlay networks
  - Delays at the servers

- With some additional assumptions, we can also extend to:
  - Multiple ISPs (and multiple Traffic Engineers)
    - Requires that users are the ones who control inter-domain routing

Conclusion

- Traffic Engineering and Content Distribution may result in **conflicting** and **unanticipated** decisions by the relevant parties

- With the use of **Pigovian taxes**, the objectives of the users and the Traffic Engineer may be aligned
  - When objectives are aligned, the equilibrium outcome is **predictable** and **optimal**

- These considerations may aid in the design of content distribution systems

Related Work

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