Evolution of the Internet Ecosystem

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Motivation

Many Internet evolution models exist. Why another one?

There is none which would be simultaneously
- realistic
- parsimonious
- having all its parameters measureable
- analytically tractable
- “closing the loop”

Only a model satisfying all these requirements can shed some light on how the Internet really evolves
All ASs can roughly be split into two classes: ISPs and non-ISPs.

New ASs can preferentially attach to ISPs, but they cannot connect to non-ISPs at all, as those do not provide Internet connectivity services.

A majority of ASs (~70%) are non-ISP.

Multiclass preferential attachment: PA + Internet-specific modification
The two key observations

- This simple modification of PA captures a bulk of the Internet topology properties.
- All other improvements and modifications (such as peering, bankruptcy, multihoming, geography, etc.) lead to much finer corrections.
**ISPs vs. non-ISPs**

- Time unit: 1 new ISP
- Non-ISPs per time unit: \(\rho\). The measured value of \(\rho\) is \(\rho = 7/3\)
- Analytic solution for the degree distribution yields \(P(k) \sim k^{-2.3}\)
- In the real Internet \(P(k) \sim k^{-2.1}\)
Finer adjustments

- **Peering:** peering links per time unit
  \( c = 0.70 \)

- **Sibling links:**
  \( \mu \approx 0 \)

- **Multihoming:**
  - ISP’s average number of providers
    \( \nu \approx 2 \)
  - non-ISP’s average number of providers
    \( m = 1.86 \)

- **Analytic solution**
  \( \gamma = 2.1 \)

- **Real Internet**
  \( \gamma = 2.1 \)
Annotated graphs

$k=8$

$k=(k_r,k_g,k_b)=(1,3,4)$

$k=5$

$k=(1,2,2)$

$k'=6$

$k'=(3,1,2)$
Model validation

- Reproducing the joint degree distribution (JDD) of the AS Internet annotated with AS business relationships captures all its other properties in synthetically generated networks.

- Simulate the model with all its parameters equal to their measured value and compare the JDDs in the modeled networks and the Internet.
Validation results
Conclusion

- The Internet appears to evolve according to preferential attachment
  - Preferential attachment, with minor Internet-specific corrections, suffices to explain virtually all properties of the Internet AS-level topology and its evolution
- Most links are from customer to provider ASs
- Therefore to make a step forward and connect our model to “real economics,” one needs to explain how customers select their providers
- Popularity of providers, their “brand names,” may be a real explanation of preferential attachment in the Internet