Computer Science, Texas A&M University

# Wealth-Based Evolution Model for the Internet AS-Level Topology


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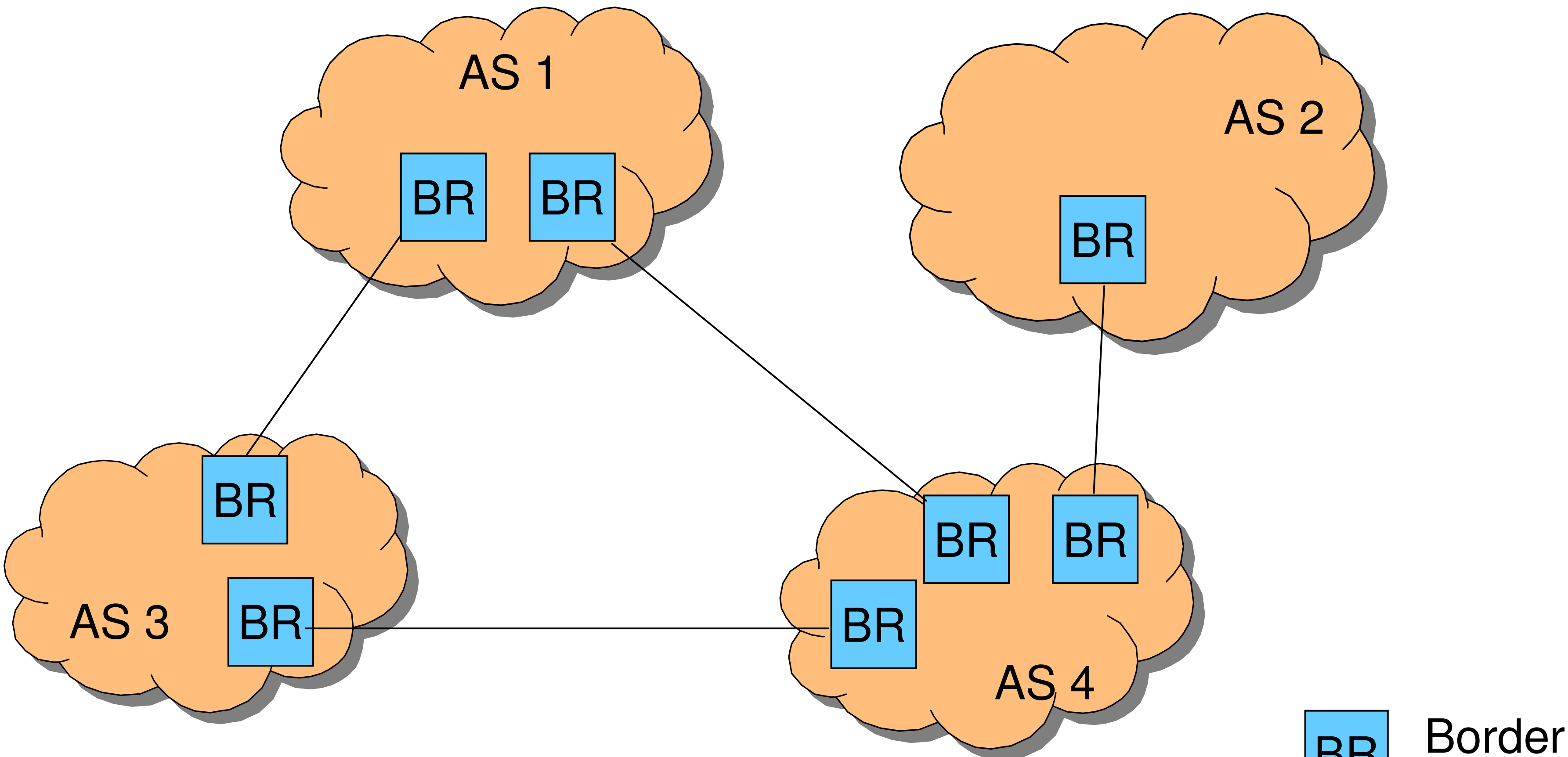
# Agenda

- Introduction
  - Topology modeling
  - Metrics
- Background
  - Preferential attachment
  - Optimization-based method
- Wealth-based Internet Topology (WIT)
  - Power-law degree distribution
  - High clustering
  - Simulations
- Wrap-up

# Introduction – Internet AS Structure

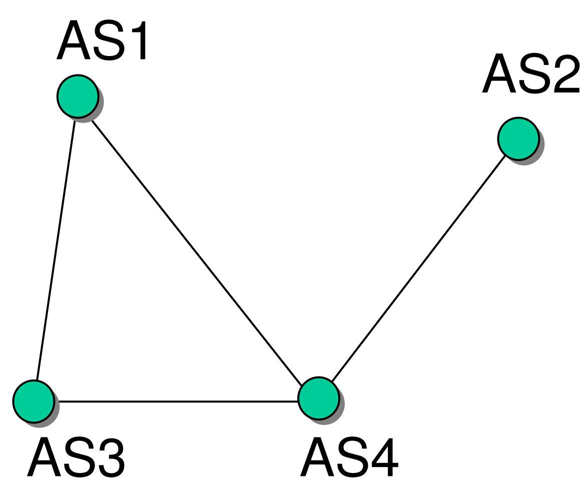
- The Internet is a network of *Autonomous Systems* (AS)




Internet AS-Level Structure

# Introduction – Internet AS Structure

- The Internet is a network of *Autonomous Systems* (AS)
- Graph representation:
  - AS → node
  - Peering relationship → edge

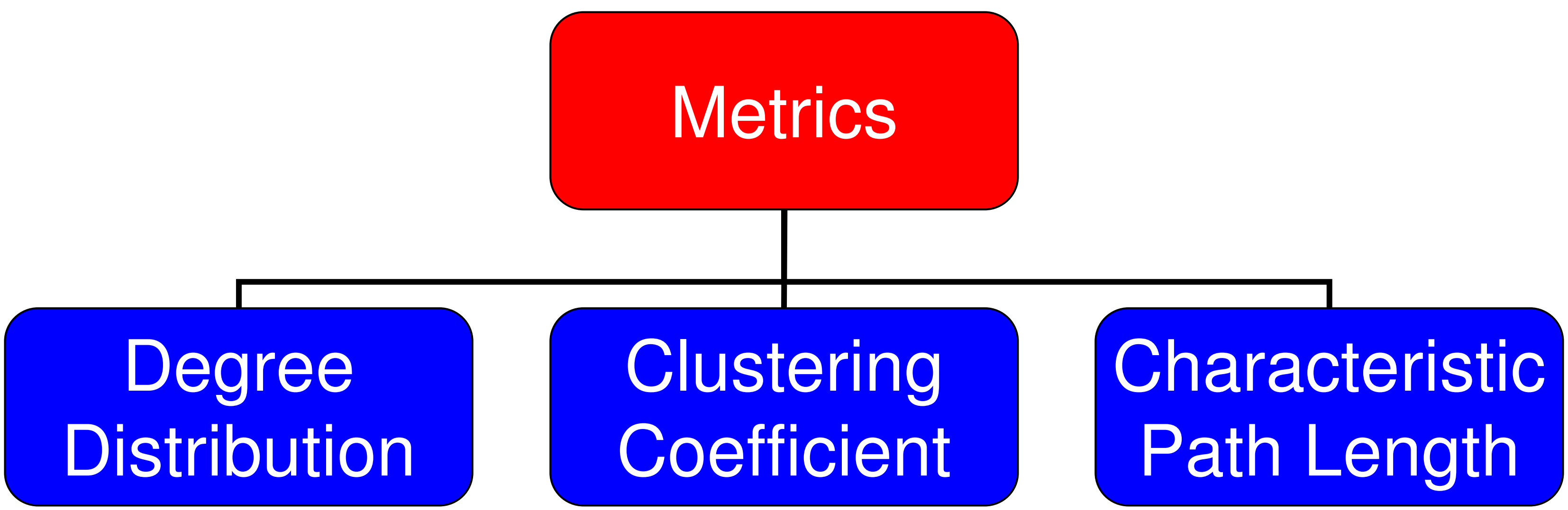


# Introduction – Internet AS Structure

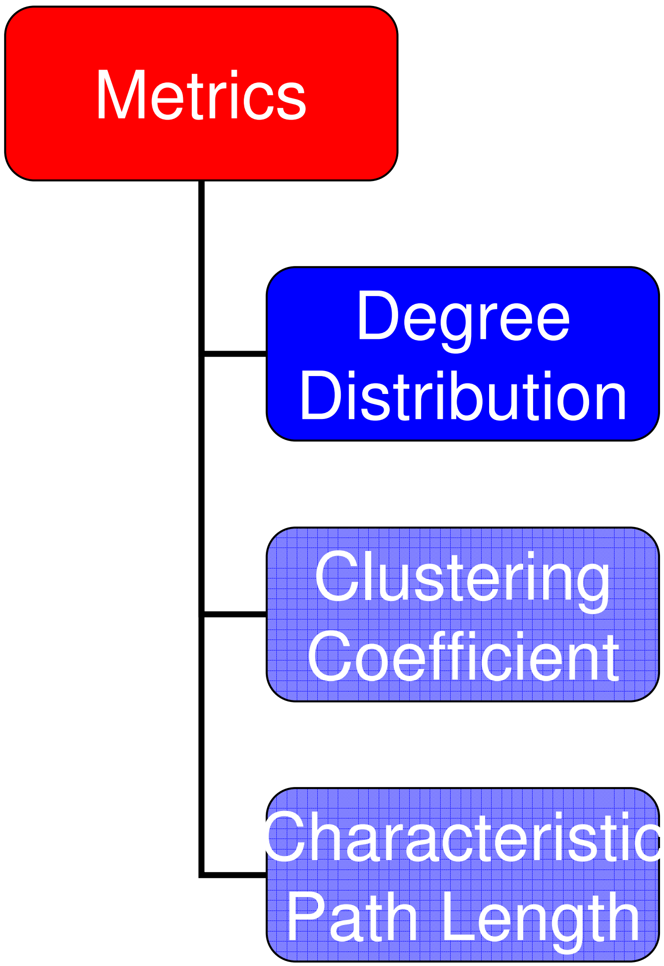
- The Internet is a network of *Autonomous Systems* (AS)
- Graph representation:
  - AS → node
  - Peering relationship → edge
- Two goals of topology models
  - Construct random graphs that resemble the Internet AS-level structure
  - Understand principles that govern Internet evolution

# Modeling Internet Topology – Application

- Topology modeling provides a convenient way to evaluate network protocols
  - Congestion control, QoS and security design, etc.
- How accurately can we mimic the Internet's topology?



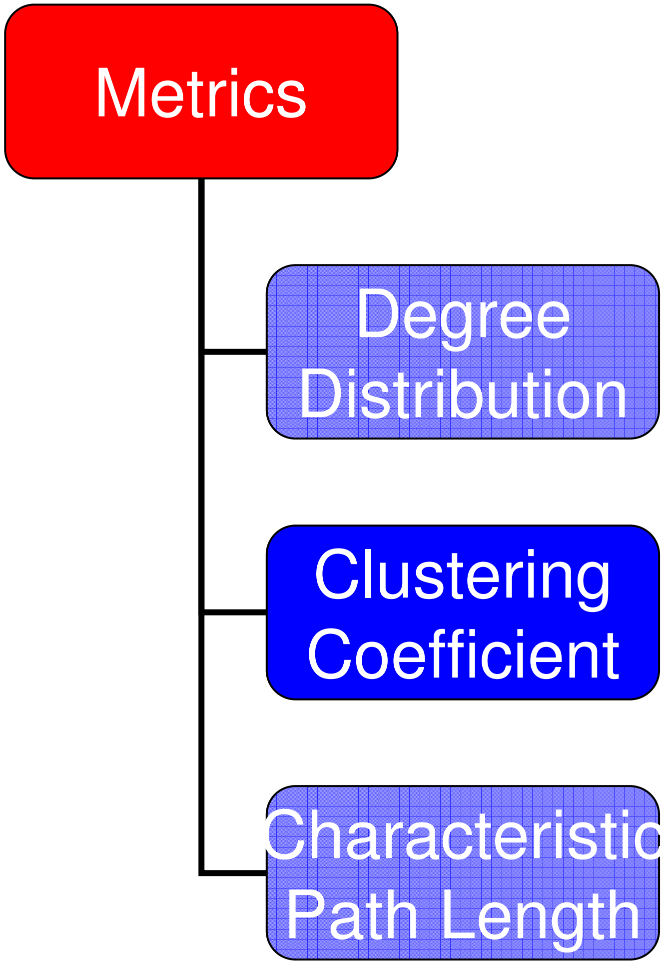
# Modeling Internet Topology – Metrics




- Faloutsos 1999
  - Noticed power-law degree distribution of the Internet

$$P(d_i > x) = (x/\beta)^{-\alpha}$$

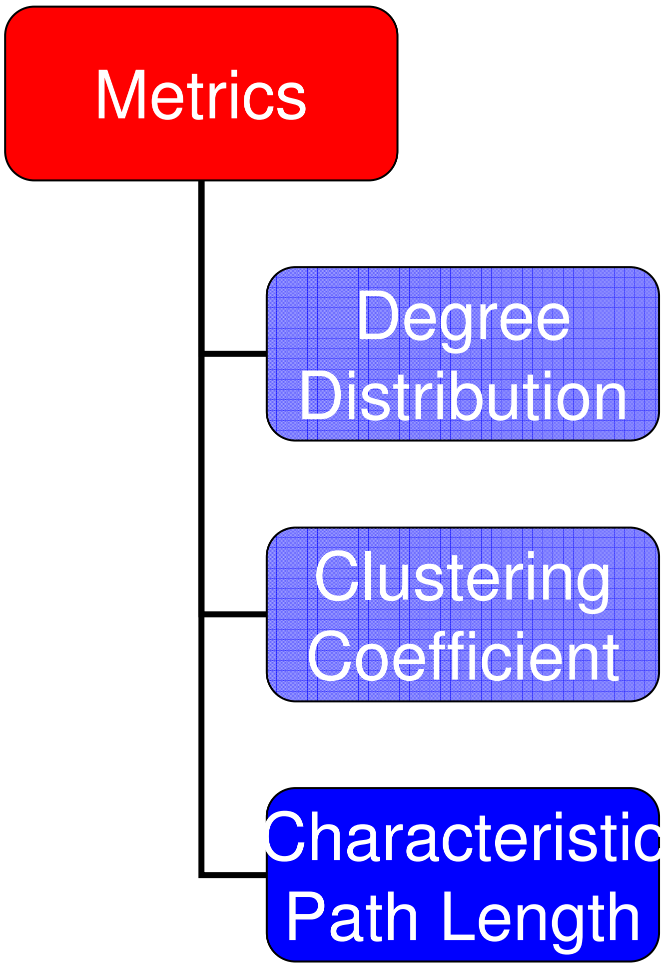
# Modeling Internet Topology – Metrics




- Measures how frequently neighbors of a node are connected

$$\gamma_i = \frac{\#\ \text{triangles}}{\#\ \text{possible triangles}}$$

# Modeling Internet Topology – Metrics




- Define $h_i$ as the average shortest path length from node $i$ to all other nodes

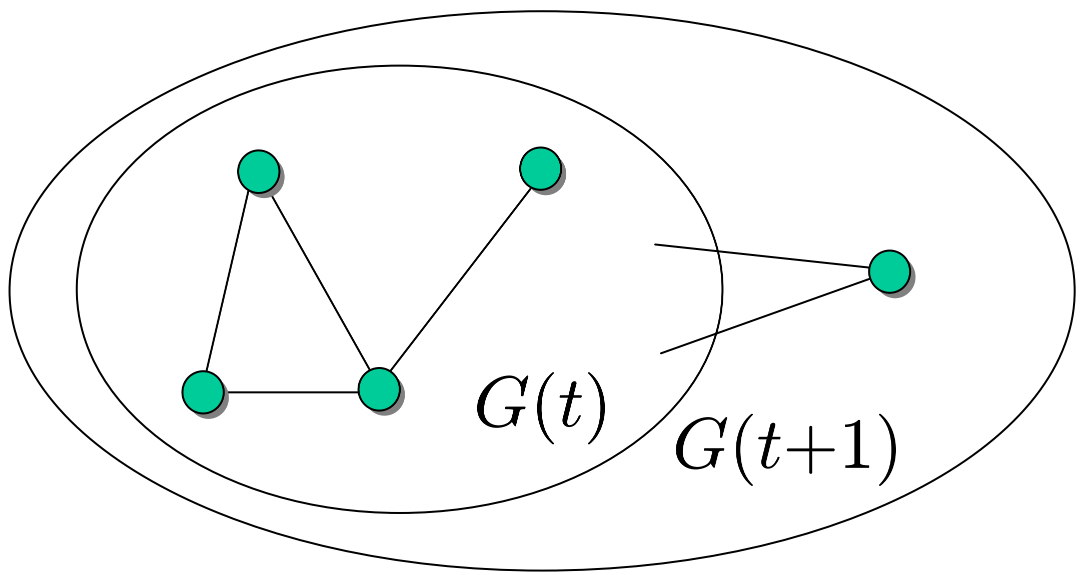
$$L = \text{median}_i\{h_i\}$$

# Methodology – Evolutionary View

- Previous efforts evaluate graph models by their static structure
  - Generate a graph of fixed size
  - Compare it with the Internet structure
  - Omit what happens during construction
- A topology model could match the Internet structure at a specific time
  - As time elapses, the match might degrade
- Solution
  - Take an evolutionary view

# Methodology – Evolutionary View

- Consider an algorithm $A$
  - Incremental growth
  - Graph $G(t)$'s properties as functions of $t$



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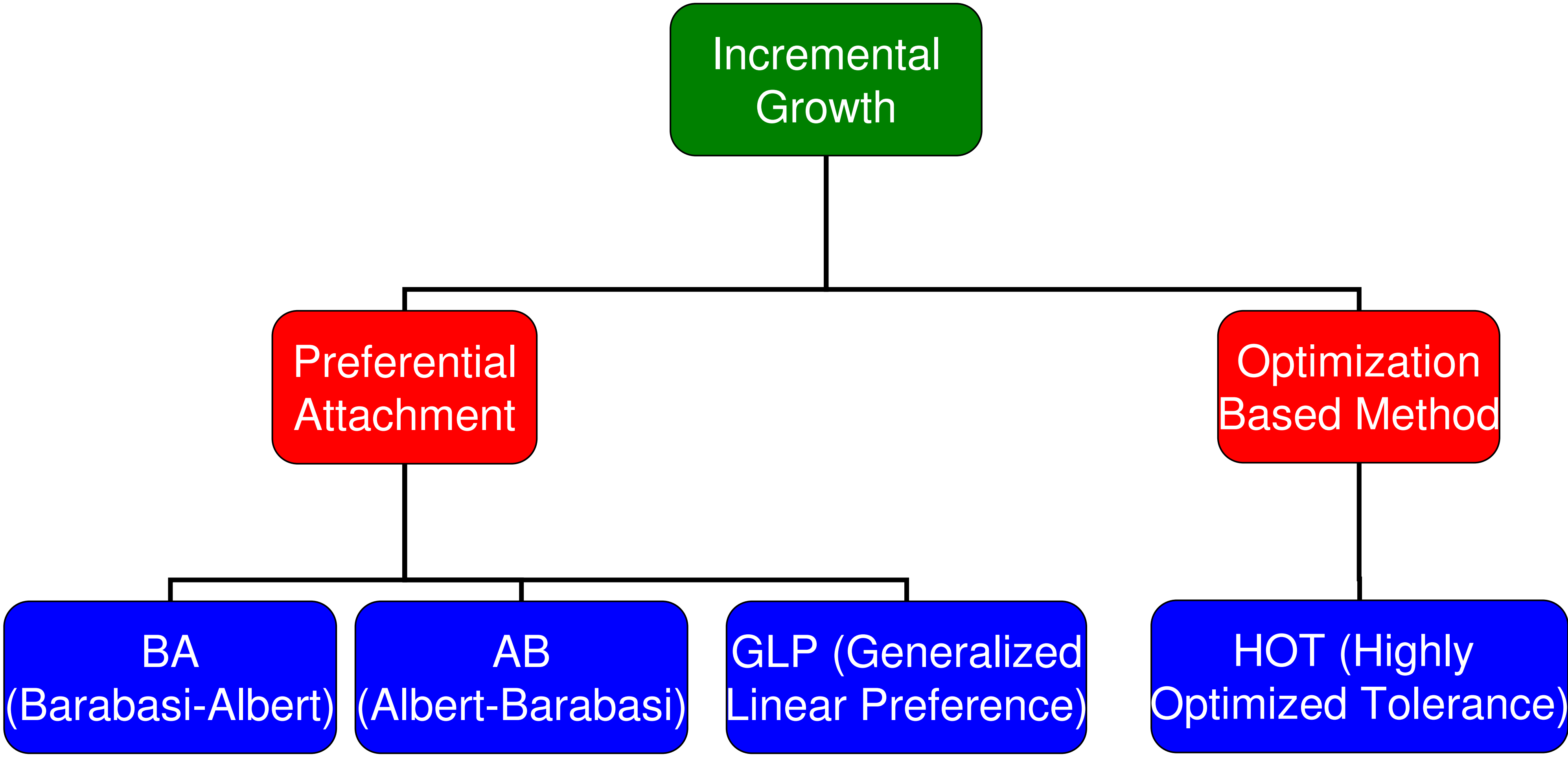
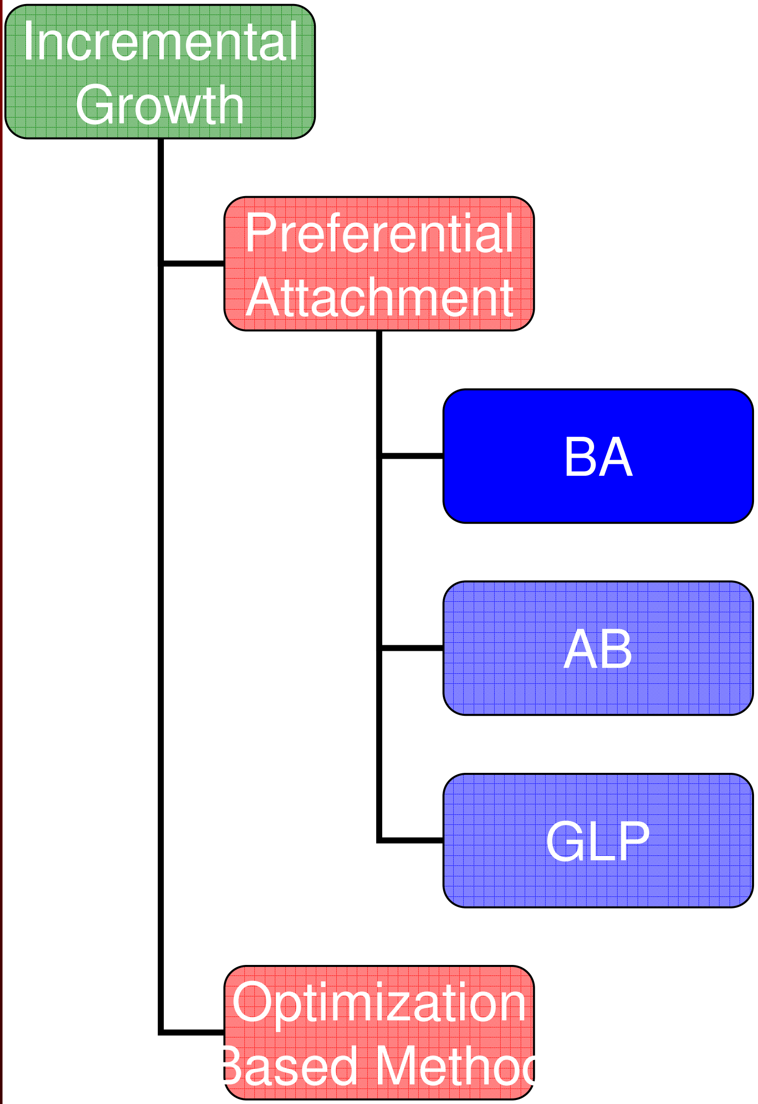
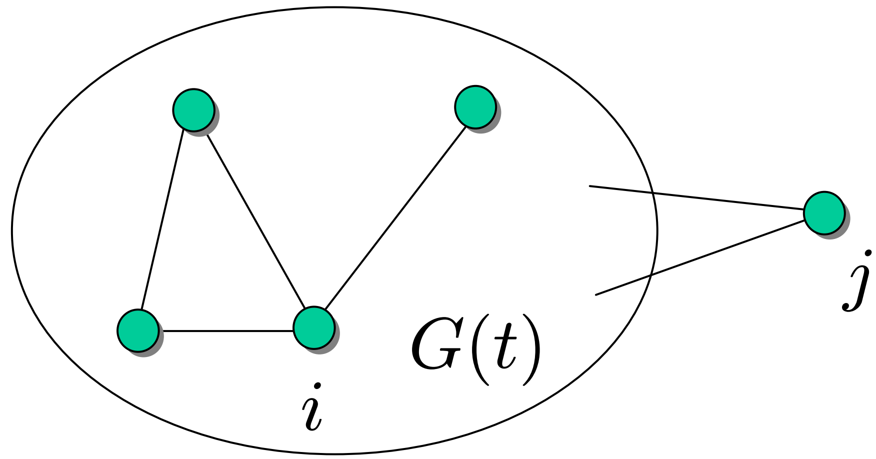
# Background – Two Major Theories



# Background – Preferential Attachment

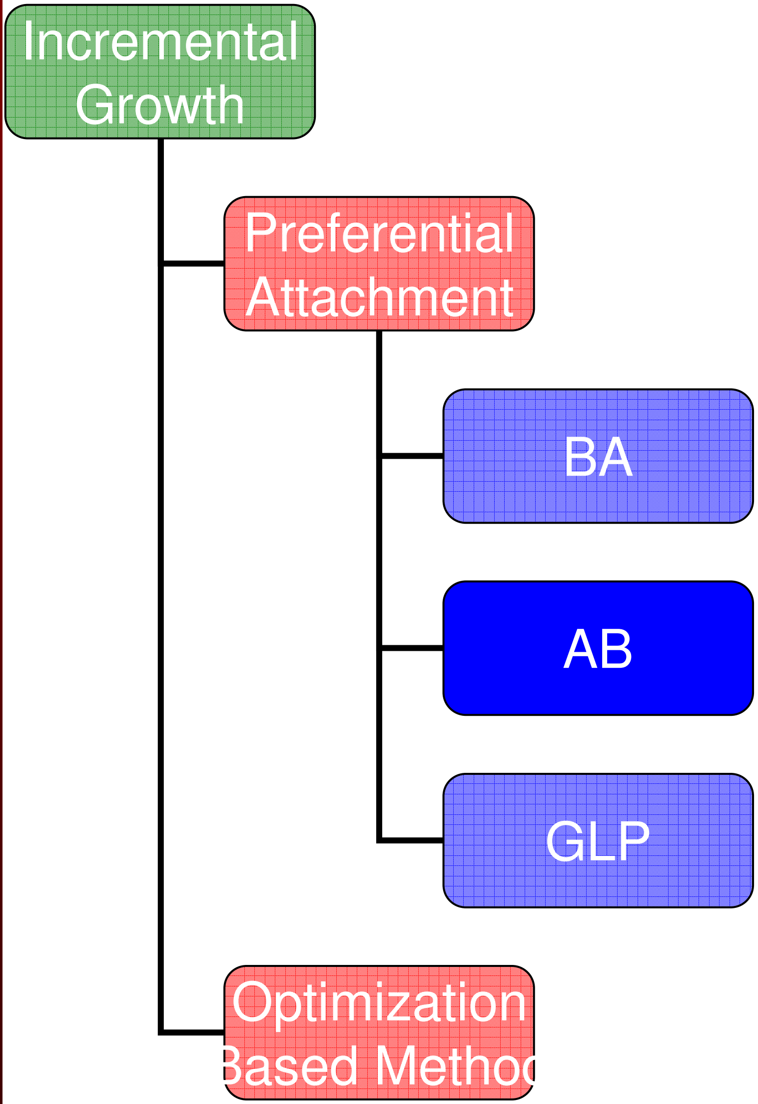


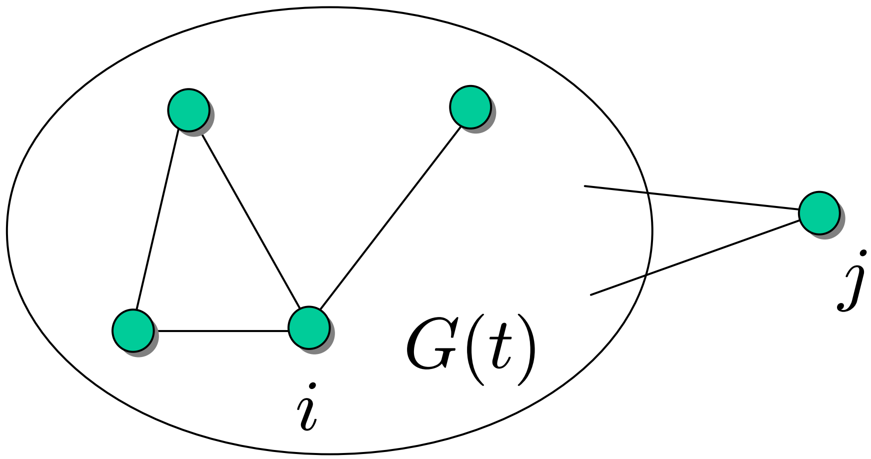




- Large-degree nodes are more attractive
- $p_i(t)$: probability of choosing node $i$ as a neighbor at time $t$

$$p_i(t) = \frac{d_i(t)}{\sum_{k=1}^{n(t)} d_k(t)}$$

# Background – Preferential Attachment

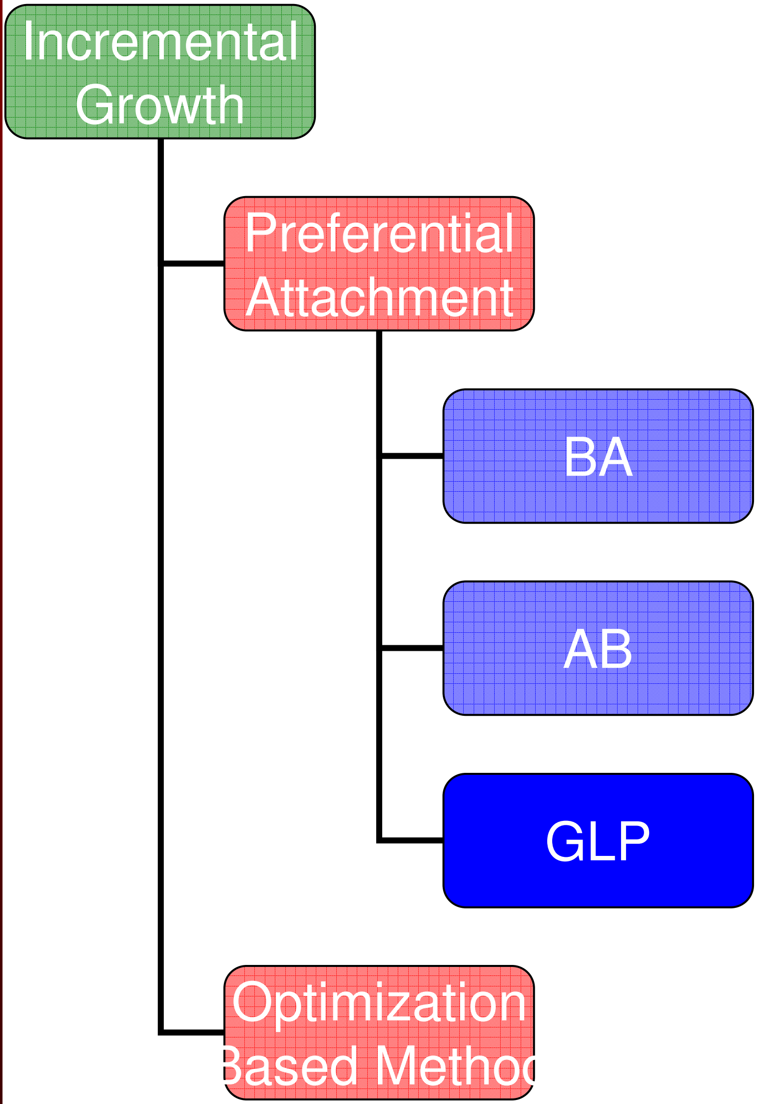


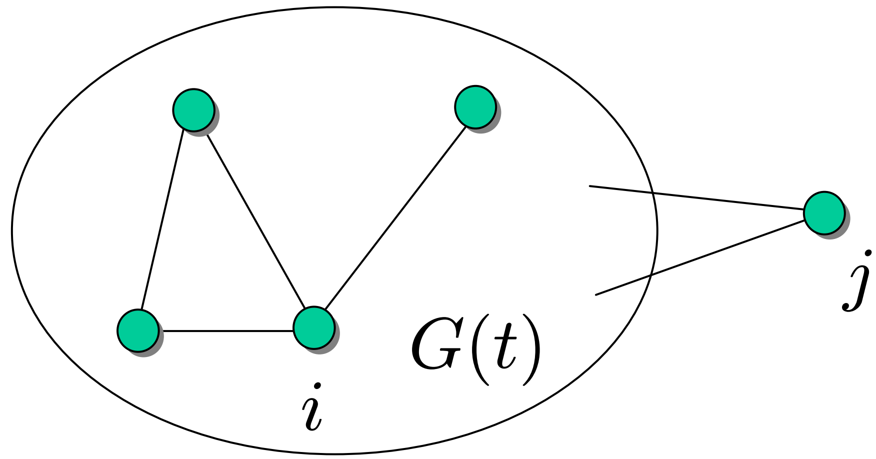




- Large-degree nodes are more attractive
- $p_i(t)$: probability of choosing node $i$ as a neighbor at time $t$

$$p_i(t) = \frac{d_i(t)+1}{\sum_{k=1}^{n(t)}(d_k(t)+1)}$$

# Background – Preferential Attachment

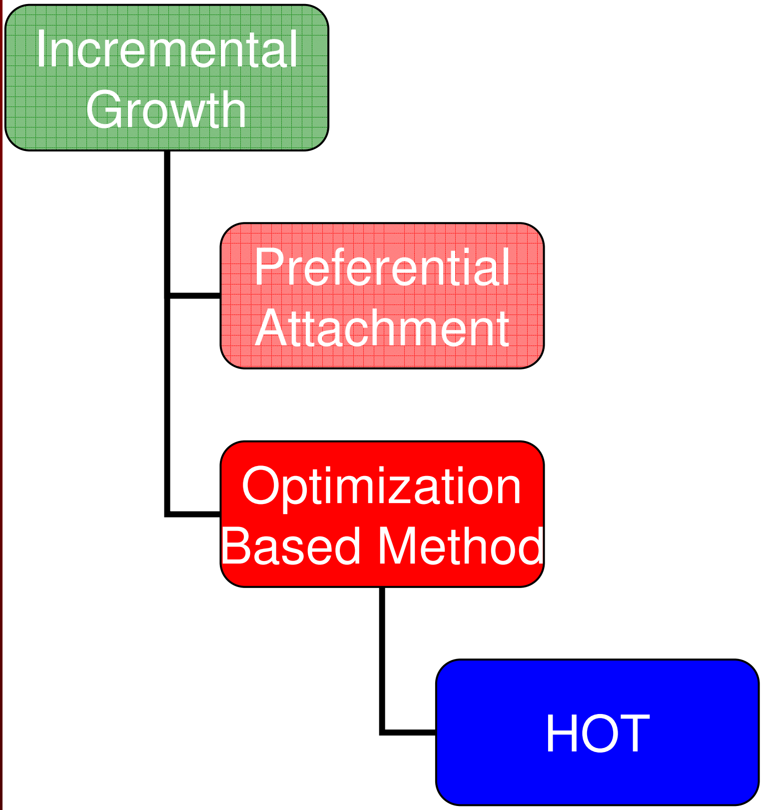


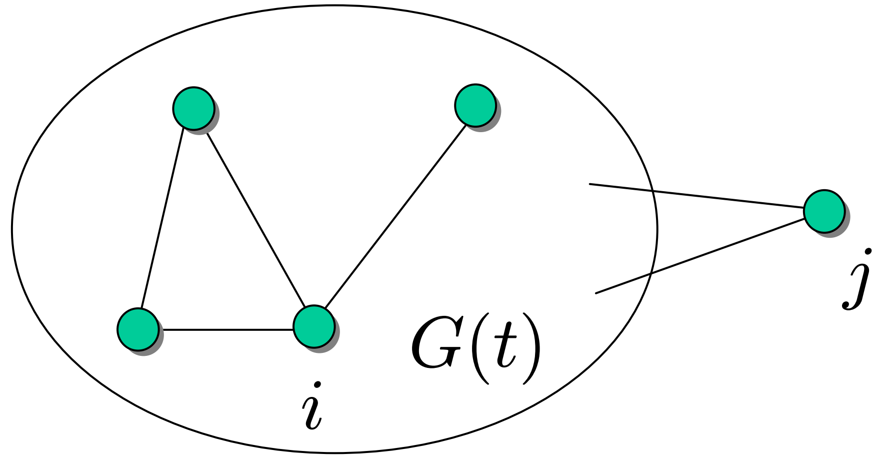




- Large-degree nodes are more attractive
- $p_i(t)$: probability of choosing node $i$ as a neighbor at time $t$

$$p_i(t) = \frac{d_i(t) - \lambda}{\sum_{k=1}^{n(t)} (d_k(t) - \lambda)}$$

# Background – Optimization




- $f_i$: cost of node $i$
- Choose $i$ with minimal $f_i$ to build link with
- $r_{ij}$ - geographical distance
  $h_i$ - average shortest path length

$$f_i(t) = \theta r_{ij} + h_i \ \ (\theta > 0)$$

# Limitations

- Preferential attachment
  - Too much emphasis on ISP popularity
  - No awareness of other factors
    - Geographic location, technical feasibility, business strategies, economic considerations, etc.
- HOT
  - Lack of mutuality
  - No economic basis
- Both require global knowledge
  - Do not explain how the Internet could have achieved its current state using decentralized actions of ISPs

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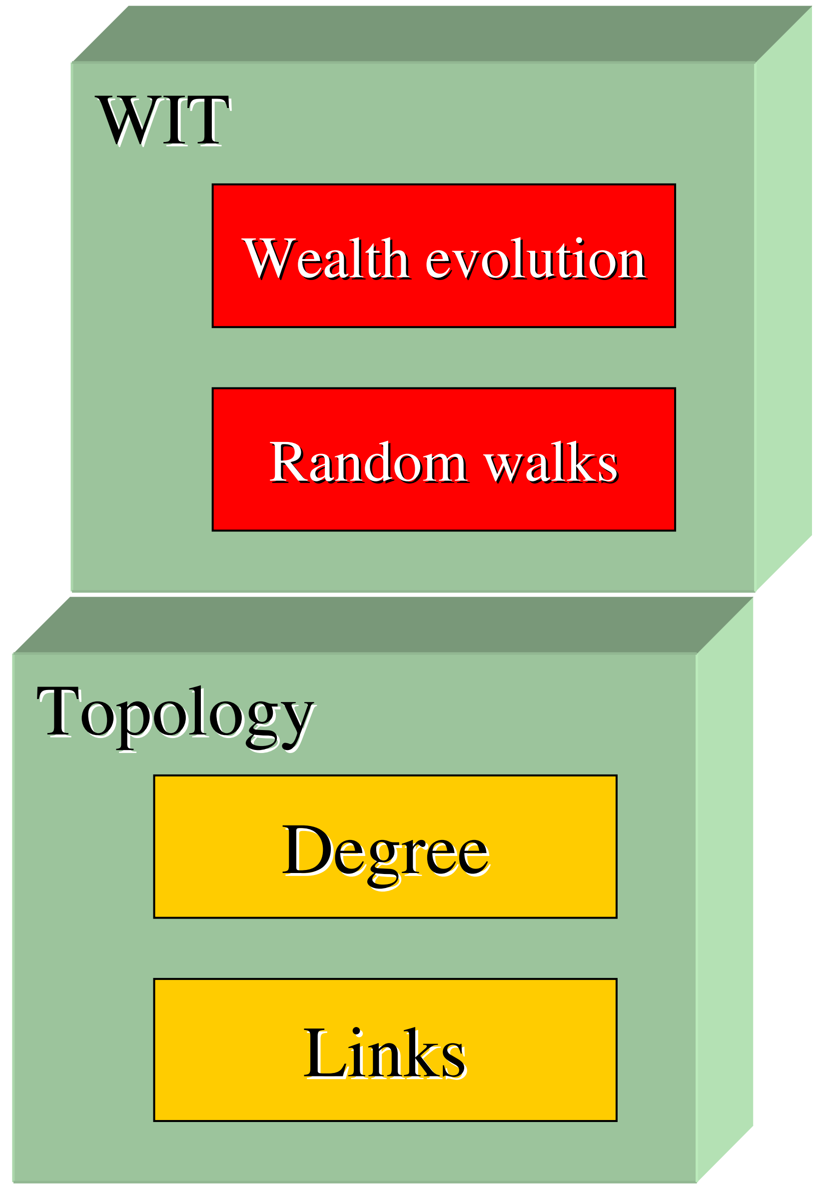
# WIT Overview

- Two elements in topology generation
  - What determines degree?
  - How to find neighbors?
- WIT provides two paradigms
  - Wealth evolution
  - Random walks



# What Determines ISP Degree?

- Tangmunarunkit [2001]
  - Observed that ISP size (# of routers) follows a power-law
  - Showed that AS size is correlated with its degree
- Economics
  - Great wealth implies large size
- Pareto [1897]
  - Individual/company wealth is power-law distributed
- To some extent, wealth determines degree

# Wealth Determines Degree

- This correlation can be explained by many factors
  - Cost of link maintenance, customer pressure, QoS objectives, etc.
- Stochastic multiplicative process from economics $w_i(t) = \lambda_i(t) w_i(t-1)$
  - $w_i(t)$: wealth of ISP $i$ at time $t$
  - $\lambda_i(t)$: randomness in income
  - Initial wealth $w_i$(join time) $= s$
  - Bankruptcy condition $z$ $(z>s)$
    - Once $w_i(t)<z$, ISP $i$ is removed from the system

# WIT Results – Wealth and Degree

- Theorem 1: If $E[\log \lambda_i] < 0$, WIT's wealth is power-law distributed with exponent

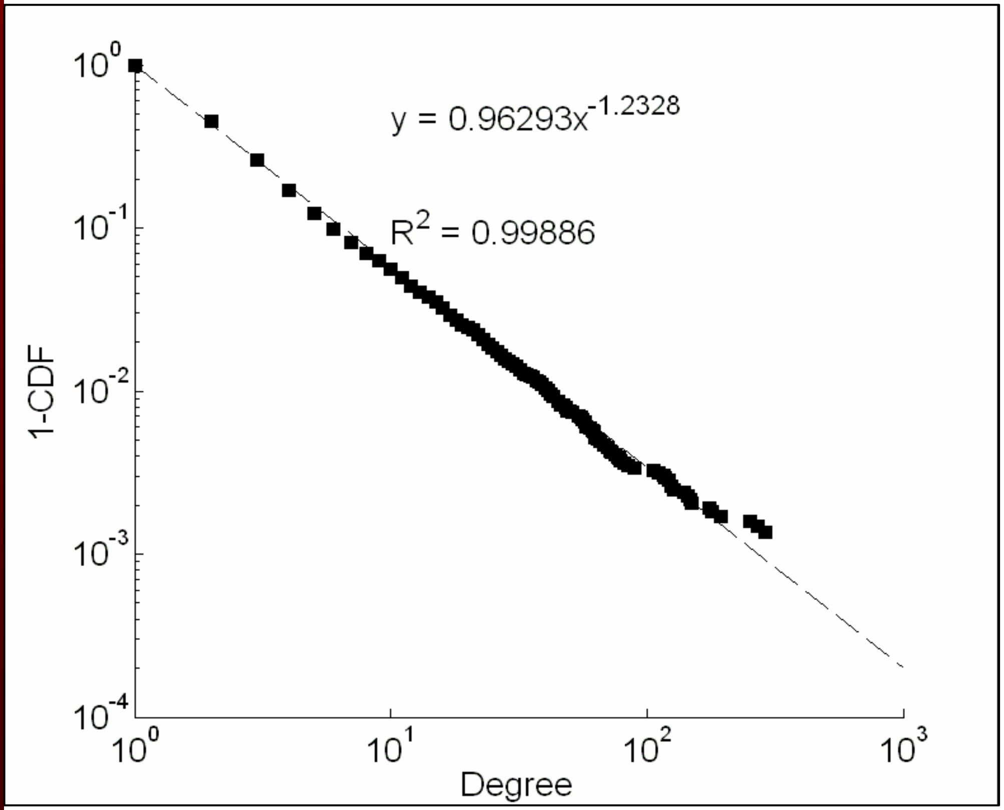
$$\alpha \approx \frac{1}{1-\xi} \qquad (1)$$

where $\xi = s/z \in (0,1)$

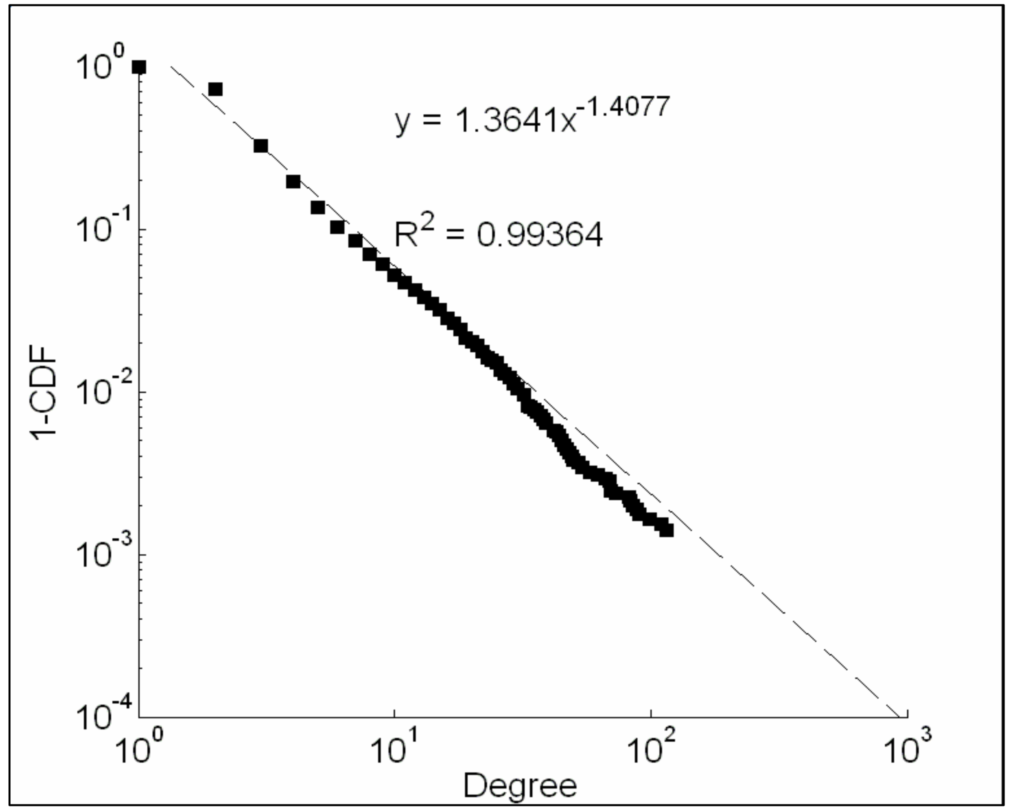
- Theorem 2: By keeping degree proportional to wealth, WIT produces power-law degree distributions with the same exponent $\alpha$ as in (1)

# WIT Simulations – Degree Distribution

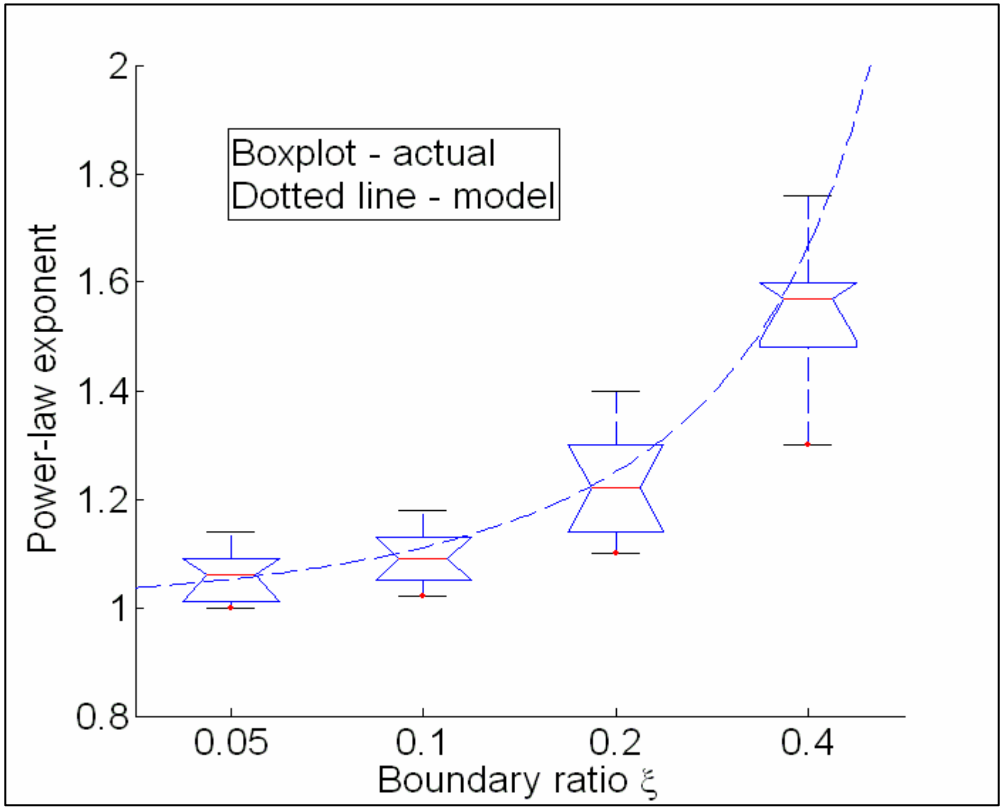
$\xi = 0.2$




$\xi = 0.4$

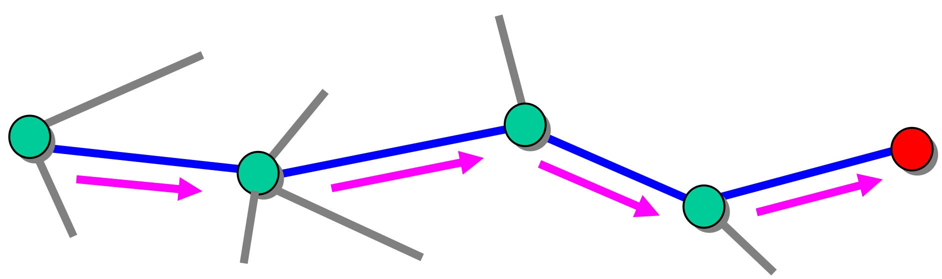


# WIT Simulations – Degree Distribution

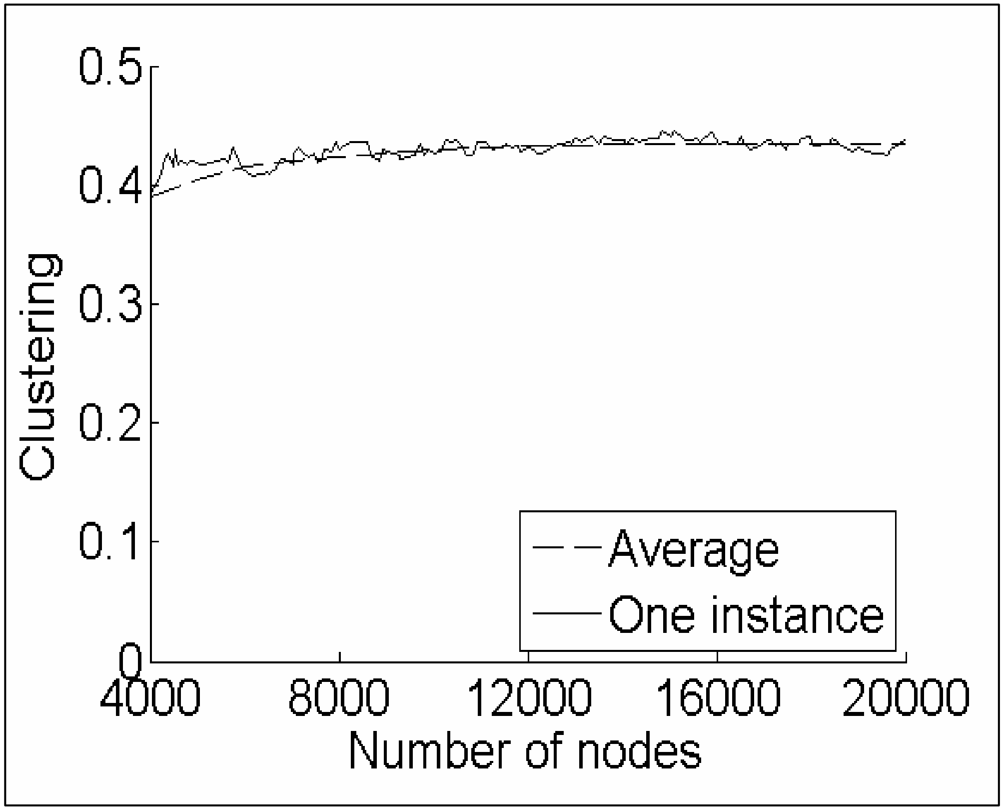


# How to Find Neighbors?

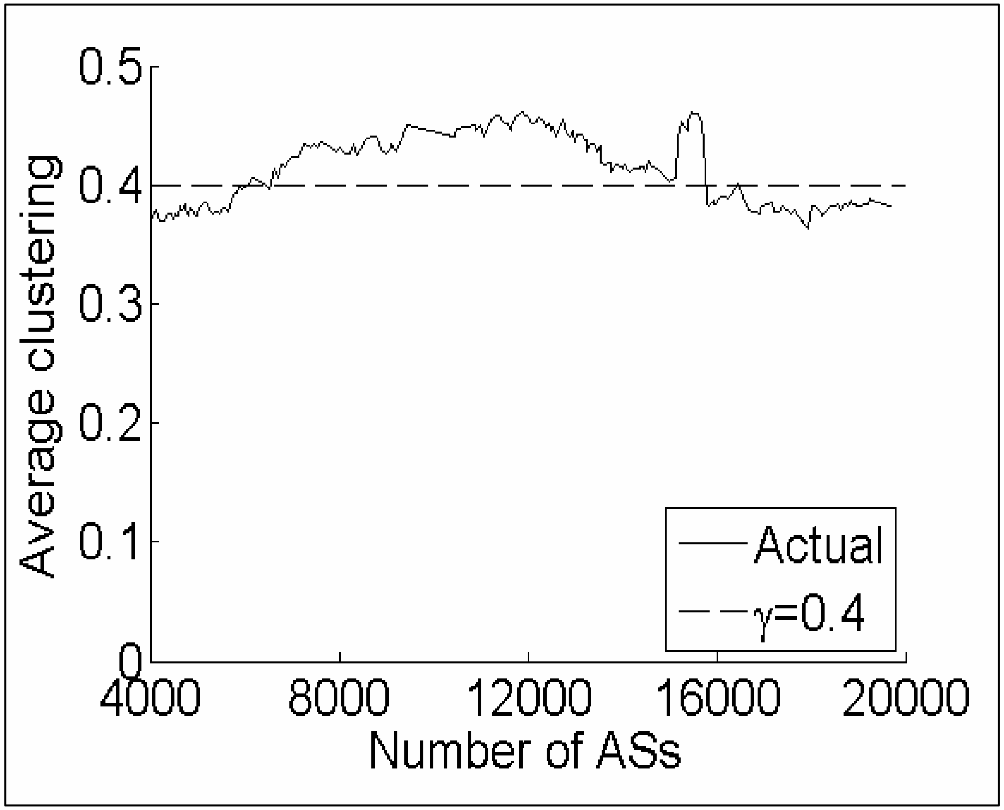
- The Internet evolves in a distributed fashion
  - ISPs make decisions based on local information
  - PA and HOT require global knowledge
- The ISP market is a large social network
  - Discover new neighbors through existing links
  - Preserve geographic locality
- WIT uses random walks to model attachment decisions



# WIT Simulations – Clustering

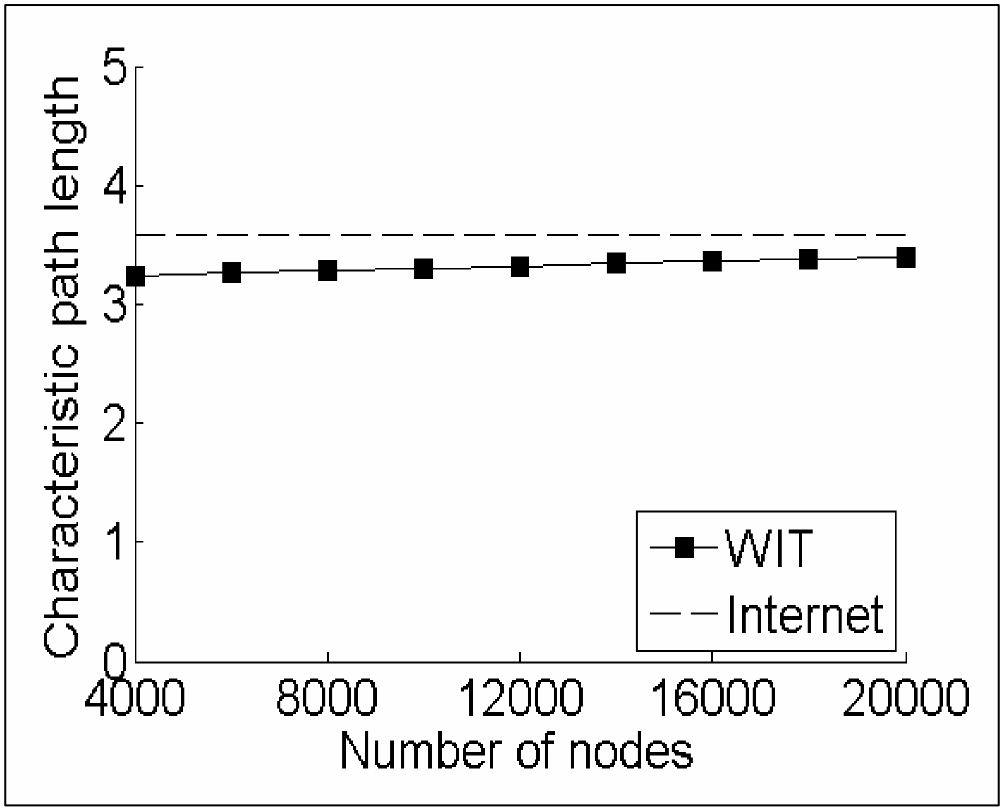



WIT

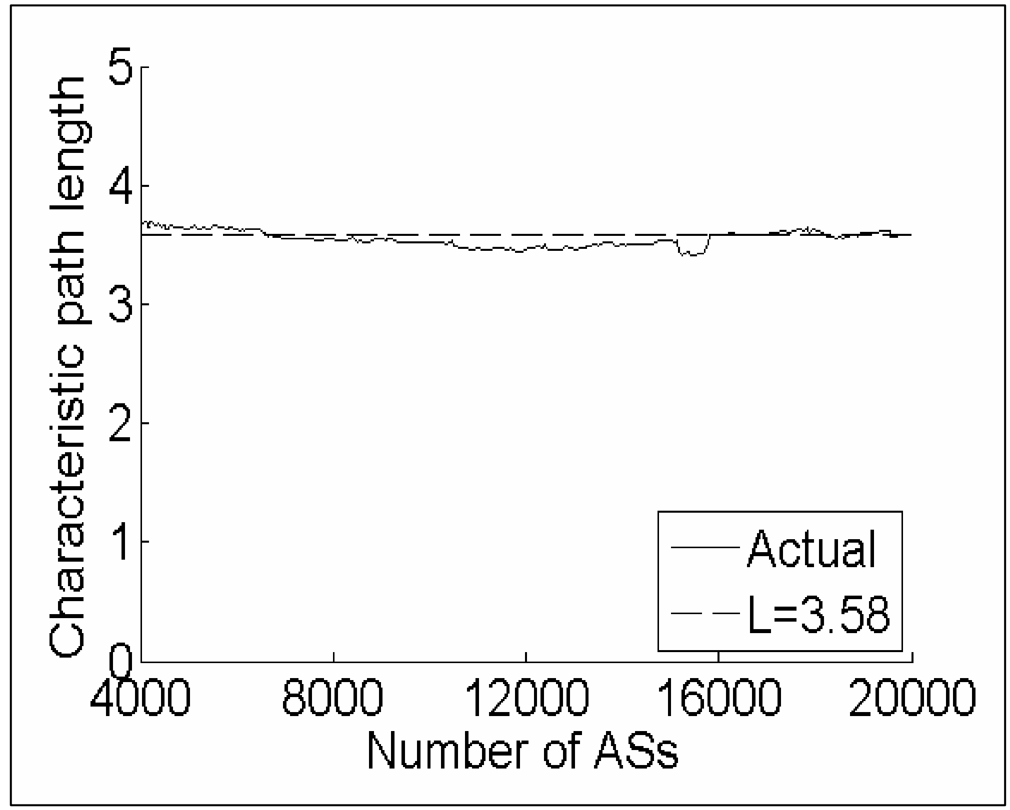



Internet

# WIT Simulations – Path Length




WIT




Internet

# Wrap-up

- Evolutionary view allows a more appropriate comparison of graph models
- Wealth-based Internet Topology (WIT)
  - Provides an alternative theory for the Internet evolution
  - Simulation results show its viability

# Wrap-up

- Additional results in the paper and technical report
  - Clustering of BA, AB, and GLP decreases
  - HOT has a very high characteristic path length that linearly increases over time
  - WIT is more accurate than the existing methods using additional metrics
    - Spectrum analysis
    - Assortativity