

# Observing the Evolution of Internet AS topology

Ricardo Oliveira  
Los Angeles

University of California,

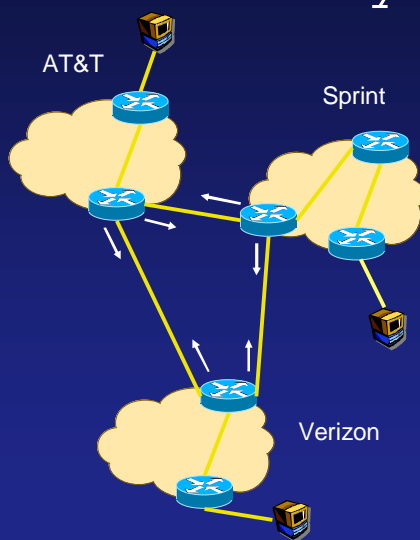
Beichuan Zhang University of Arizona, Tucson

Lixia Zhang  
Los Angeles

University of California, Los

1

## Internet and Autonomous Systems

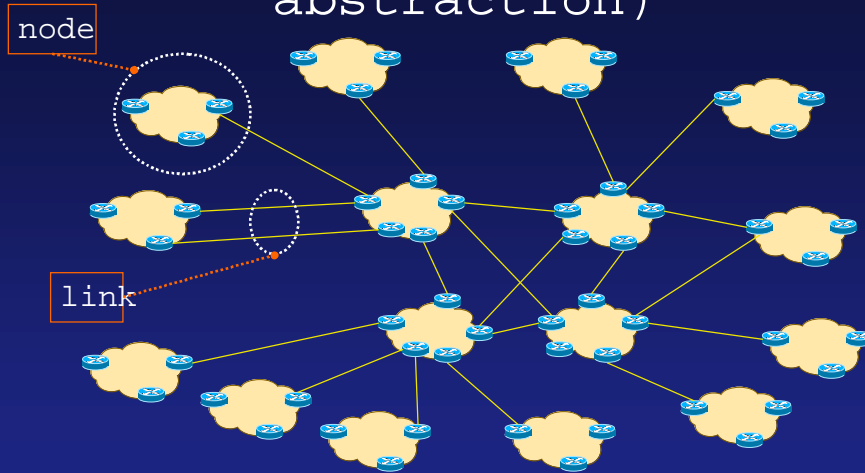


• **Autonomous System:** a set of routers or networks under the same administration

• Border routers exchange routing updates via the **Border Gateway Protocol (BGP)**

2

# Internet AS topology (the abstraction)



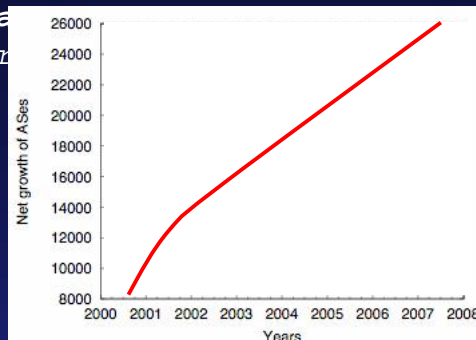
- About **26k ASes** in the Internet, at least **80k links** interconnecting them

3

*"Nothing endures but change"*  
--Heraclitus, Ancient Greek

- The network evolves over time...

In a time span of **7 years**  
the network grew in size more than **3 times**



## Why study the Evolution of the AS Topology?

- Enables projection of future needs
- Limitations of inter-domain routing protocols
- Interplay between networking technology, the resulting topology and the underlying economic forces

4

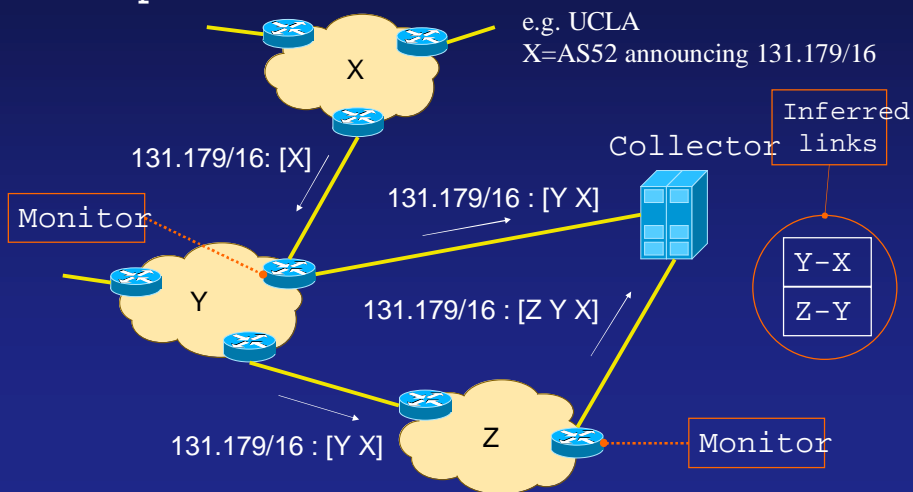
# Outline

1. Measuring the AS topology
2. The Liveness and Completeness problems
3. Modeling the appearance and disappearance of AS links
4. Model validation and the use of traceroute
5. Model Applications
6. Conclusion

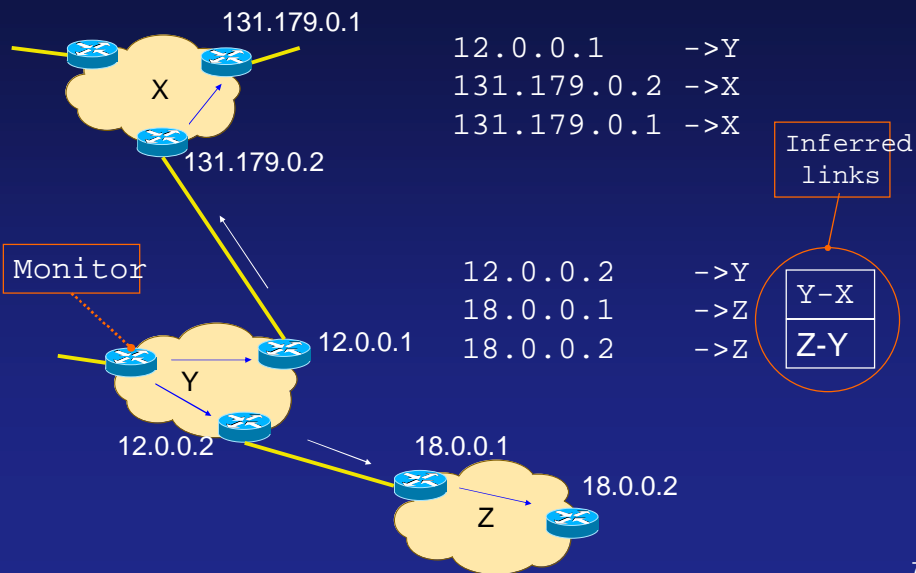
5

## Passive measurement: BGP data

- BGP is a **path-vector** protocol
- The **collector** gathers BGP **routing tables** + BGP **updates**



# Active measurement: traceroute



7

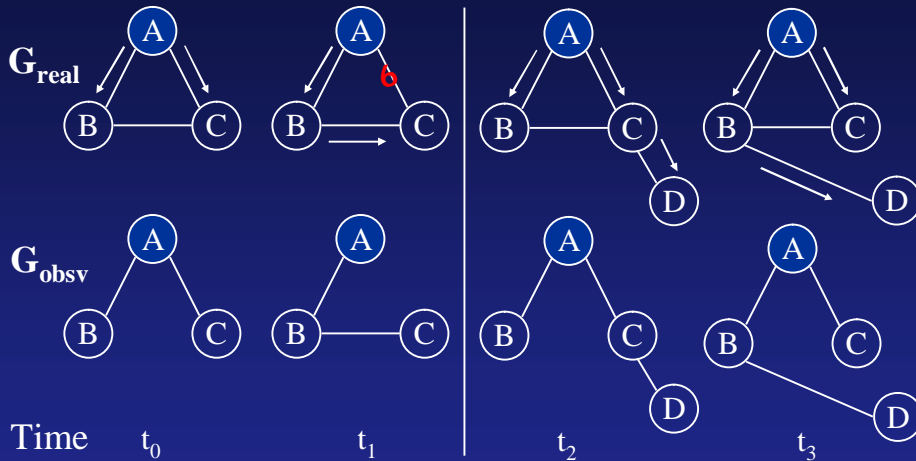
## Outline

1. Measuring the AS topology
2. The Liveness and Completeness problems
3. Modeling the appearance and disappearance of AS links
4. Model validation and the use of traceroute
5. Model Applications
6. Conclusion

8

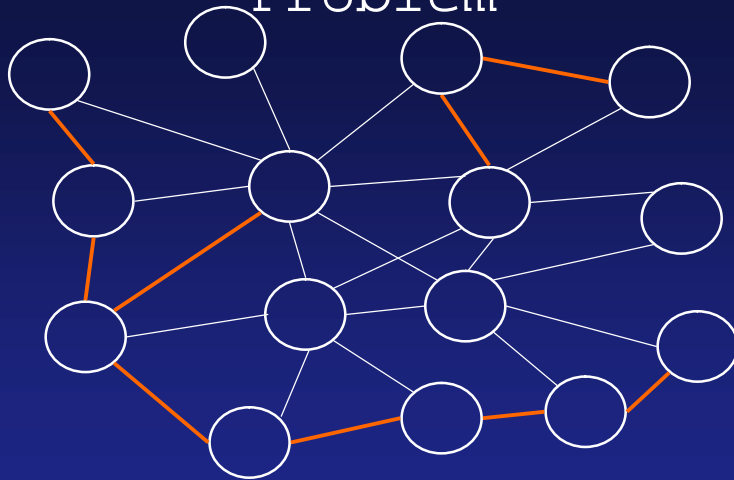
# The Liveness Problem

→ BGP path or traceroute probe from the monitor



Liveness problem: what changes in  $G_{obsv}$  correspond to changes in  $G_{real}$ ?

# The Completeness Problem



— link in  $G_{obsv}$   
 — link not in  $G_{obsv}$

The completeness problem: how much is  $G_{obsv}$  missing from  $G_{real}$  at a given time?

# Liveness and Completeness

- Considerable amount of previous work studying the **completeness** of the observed topology
  - However up to here, nobody addressed the **liveness** problem
  - Solving completeness is difficult ... but solving liveness is a step towards that direction
    - e.g. combining  $G_{\text{obs}}(t_0)$  and  $G_{\text{obs}}(t_1)$  will give more complete topology at  $t_1$ , provided we know links in  $G_{\text{obs}}(t_0)$  are still alive at  $t_1$
- In this work we formulate the **liveness** problem a solution and partially validate it

11

# Outline

1. Measuring the AS topology
2. The Liveness and Completeness problems
3. Modeling the appearance and disappearance of AS links
4. Model validation and the use of traceroute
5. Model Applications
6. Conclusion

12

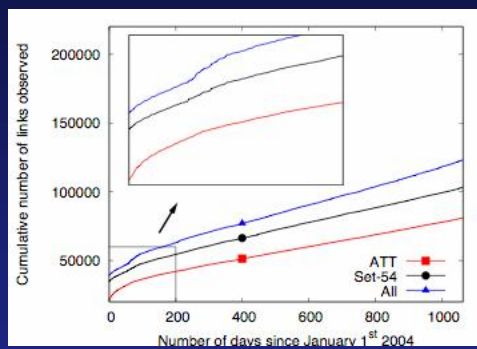
## Data Sets

About **3 years** of data from different sources

- **ATT**: single BGP monitor in AS7018
- **Set-54**: data from 54 monitors in 35 Ases present during the entire measurement
- **All**: data from all monitors

13

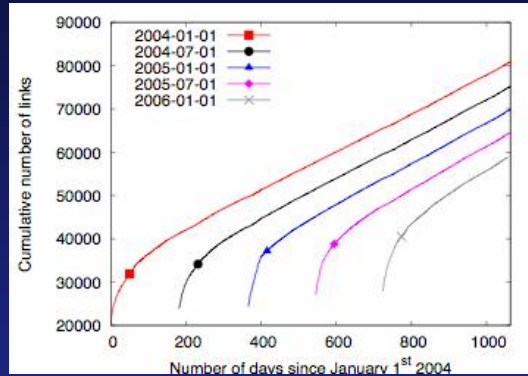
## The Appearance of Links and Nodes



All curves start w/ exponential growing rate and settle on a constant rate

14

# Starting Time Invariant



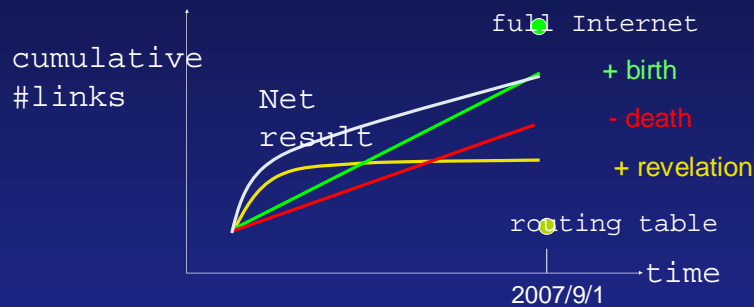
The same pattern holds for different starting

It should hint at something fundamental to topology observation

15

# Birth, Death and Revelation

Suppose we want to estimate the topology on a given day:



## Revelation

- How to model these processes?
- existing links are added along the time net are revealed by e.g. updates
- old links are removed from the Internet over time.
- revelation rate is expected to decrease over

## Modelling the appearance of links

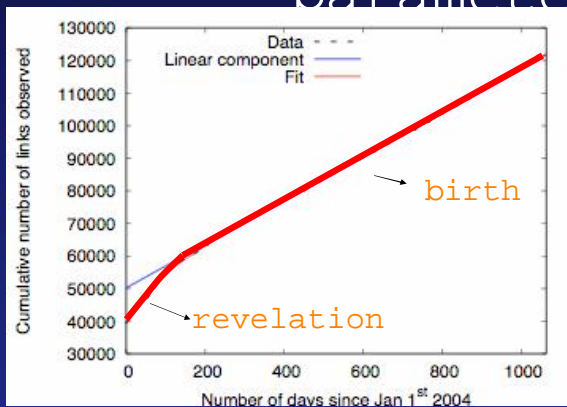
- Divide links in three types:
  - **Visible:** links that have been observed
  - **Invisible:** links that cannot be observed by set of monitors
  - **Hidden:** links possible to observe but have been revealed
- Two simple assumptions:
  - constant birth rate:
 
$$b = b_v + b_h$$
  - uniform revelation probability:
 
$$\lambda \Delta t$$
 for a small  $t$

$$\# \text{ links} = v(t) = v_0 + bt + (h_0 - \frac{b_h}{\lambda})(1 - e^{-\lambda t})$$

birth of new links
revelation of hidden links

17

## Inferring appearance parameters



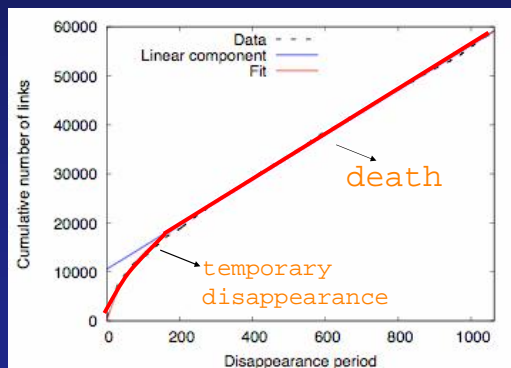
Parameter	Value
Birth rate $b$ (day <sup>-1</sup> )	67.3
Revelation rate $\lambda$ (day <sup>-1</sup> )	0.0151
$(h_0 - h_v)$	11,013

18

# The disappearance of links and nodes

- Similar model for disappearance:

$$z(t) = \frac{f_0}{m} (1 - e^{-mt}) + dt$$



Parameter	Value
Death rate $d$ (day <sup>-1</sup> )	67.3
Revelation rate $\mu$ (day <sup>-1</sup> )	0.0172
$f_0/\mu$	10,545

19

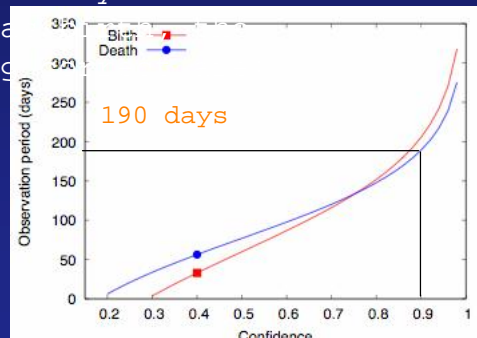
# Topology vs. transient routing changes

- Each day links appear from two sources:
  - $b_v$  from birth
  - $lh(t)$  from revelation

- If we count all newly discovered links on day  $t$  a

$$confidence(t) = \frac{b_v}{b_v + lh(t)}$$

Need long term measurements to accurately capture topology changes



# Outline

1. Measuring the AS topology
2. The Liveness and Completeness problems
3. Modeling the appearance and disappearance of AS links
4. Model validation and the use of traceroute
5. Model Applications
6. Conclusion

21

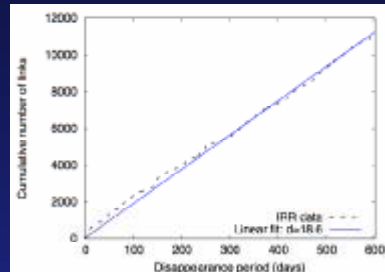
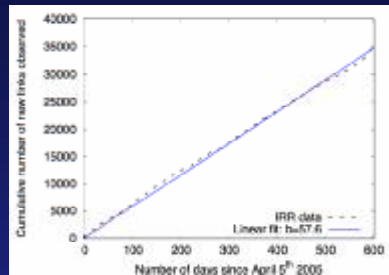
# Model validation

Used two indepent sources :

- Internet Routing Registry
- Cross verification with Skitter traceroute data

22

## Comparison w/ Internet Registry Data

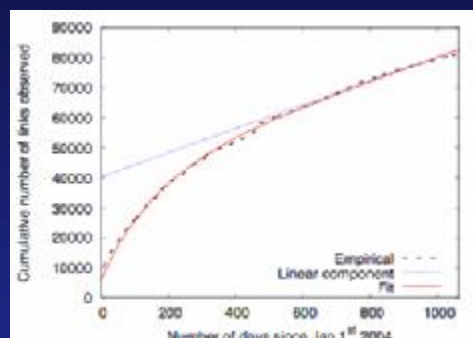


Registry data shows linear trend over time consistent with our assumptions of linear link birth and death

23

## Verification w/ Skitter traceroute data

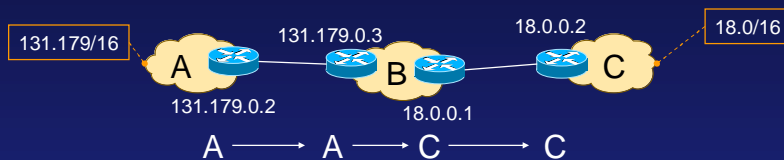
- About 20 monitors around the globe
- Fixed destination list of about 970,000 IP addresses



- Shape similar to BGP data, but some differences...
- Traceroute is slow in discovering hidden links

24

## AS connectivity inference from traceroute



Path A-B-C will be **wrongly** inferred as A-

- We contacted 20 ISPs for which Skitter reports observed in BGP, but only 4% of these links were by the operators

[ previously reported in sigcomm'03 Mao et al.

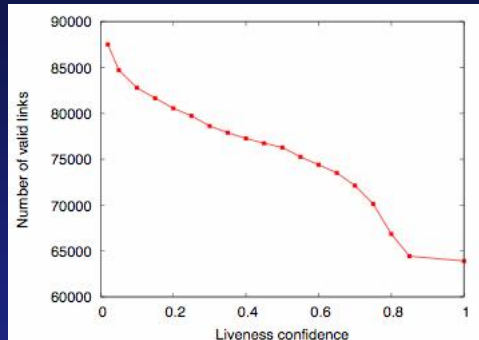
25

## Outline

1. Measuring the AS topology
2. The Liveness and Completeness problems
3. Modeling the appearance and disappearance of AS links
4. Model validation and the use of traceroute
5. Model Applications
6. Conclusion

26

## More Accurate View of the Topology



- *Static view: the liveness-completeness tradeoff in building topology snapshots*

27

## About the model

- It's mainly descriptive and not derived from **first principles**; other models may also fit the data well
- It's simple but works well
  - The model might work well due to its **macroscopic granularity** and the **large scale** of the Internet
  - may not work if considering only a **subgraph** of the network or a **different time scale**

28

## Conclusion and Future Work

- We formulated the topology **liveness problem**
- We presented a **solution** to the liveness problem and did **partial validation**
- The model calls for further investigation:
  - Why the evolution of the Internet can be approximated well by such over-simplified model?
  - Test w/ different time scales and subcomponents of the network (e.g.

29

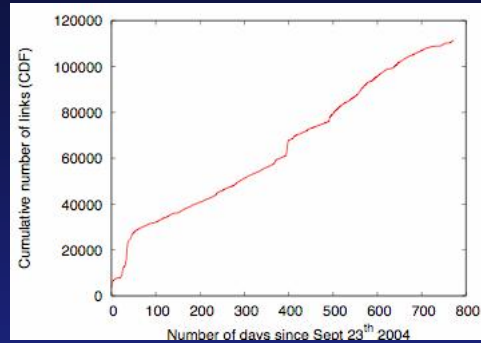
## Questions?

Thanks!

[rveloso@cs.ucla.edu](mailto:rveloso@cs.ucla.edu)

30

## DIMES



- More than **12,000 agents** tracerouting to different destination lists
- Curve is irregular due to the **variable number of agents**, from a few hundred in early 2005 to about 12,000 in late 2006

31

## How to capture topology dynamics with traceroute?

- Measurement platforms using traceroute to measure AS topology dynamics should ideally be:
  - Broad**: destination addresses should represent all Ases
  - Fresh**: destination list needs to be updated periodically
  - Frequently probed**: each destination should be probed at least each 24h

32

# Model Applications

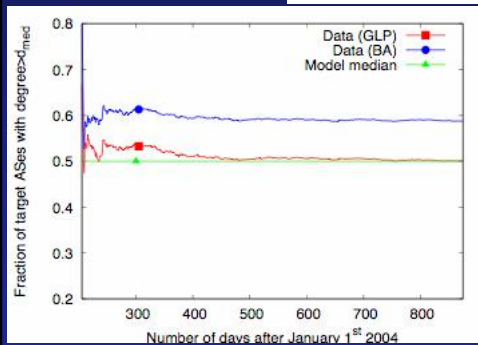
1. More accurate views of the topology
  - Static view
  - Dynamic view
2. Evaluation of theoretical models
  - E.g. preferential attachment model
3. Characterization of topology evolution trends

33

## Evaluation of preferential attachment model

- BA model describes the probability  $P(d,t)$  that a new node attaches at time  $t$  to an existing node with degree  $d$  as:

$$P(d,t) = N(d,t) \frac{d}{\sum_j d_j(t)}$$



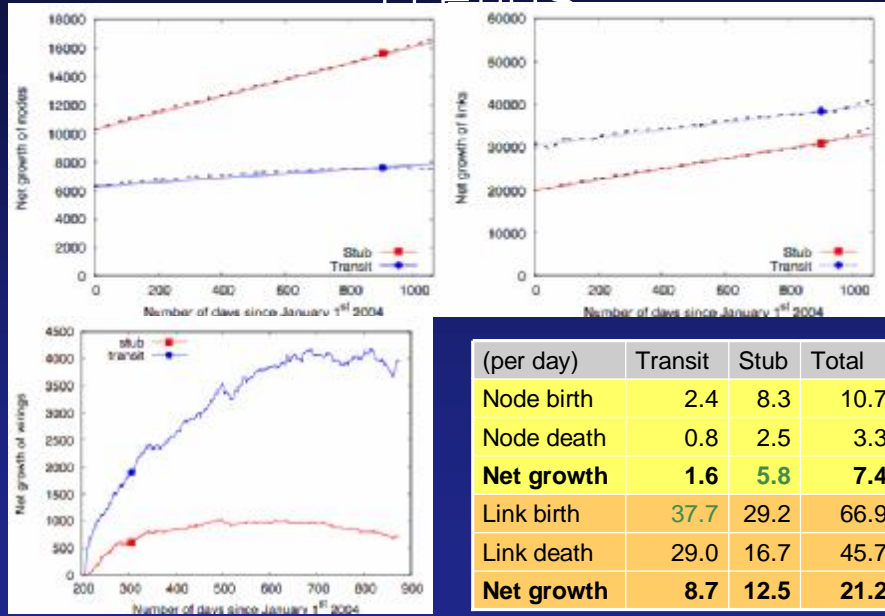
- We use our model to filter out the real attachments

- Compare data median w/ the model median

The corrected BA model (GPL) describes well the attachment probability

34

# Characterizing Evolution Trends



35