

# Influence of Route Choice Behavior on Vulnerability to Cascading Failure in Transportation Networks

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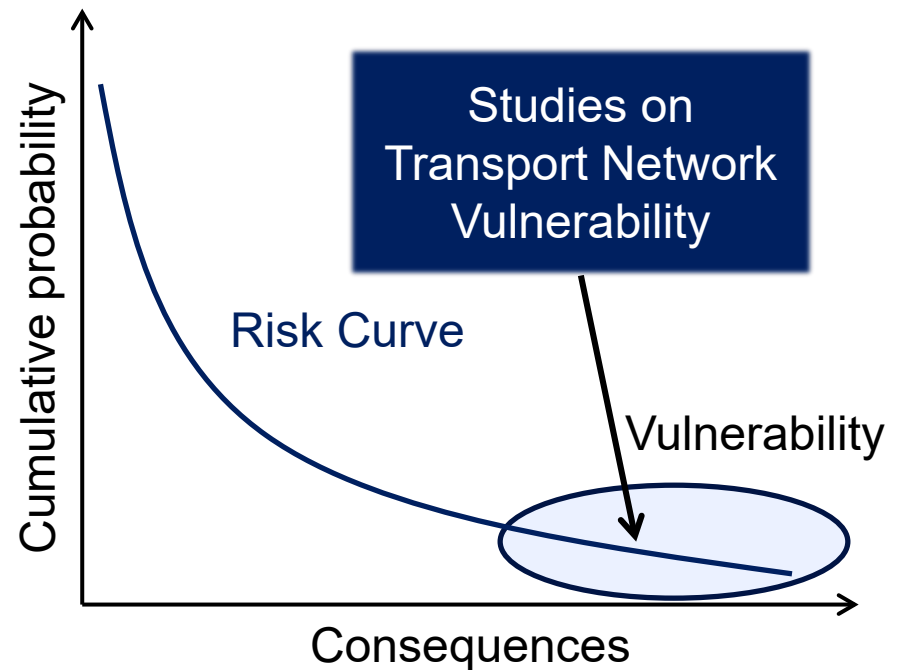
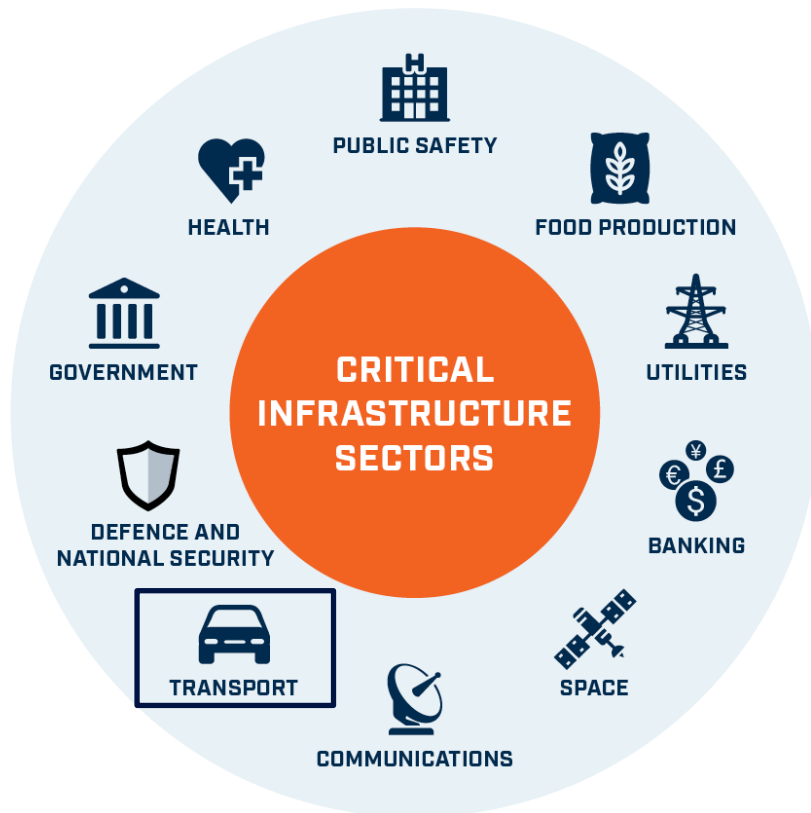
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# Transport Vulnerability

- Transportation network: one of critical infrastructures supporting the movement of people and goods
- Catastrophic events sometimes occur in transport networks
- **Transport network vulnerability** has been studied intensively in recent years



from Mattson and Jenelius (2015)

# Cascading Failure in Complex Networks

- Network vulnerability has also been studied in **complex networks**
- One topic is **cascading failure** mainly discussing following phenomena (Barabasi, 2016)



Blackout



Communication Disturbance



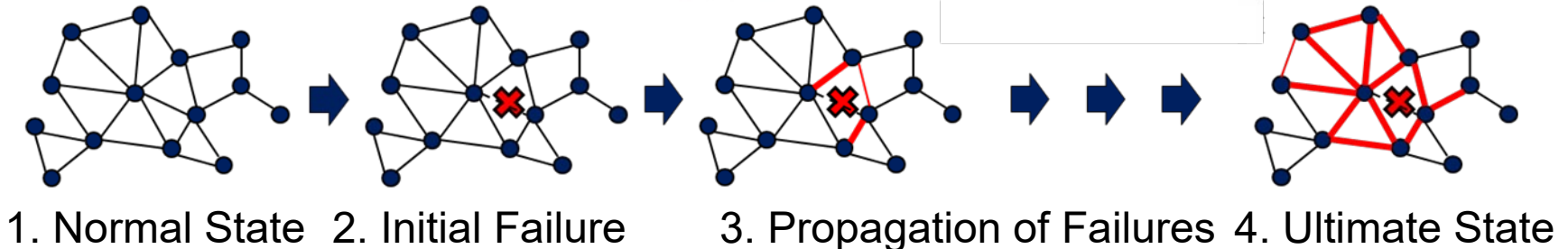
Financial Crisis



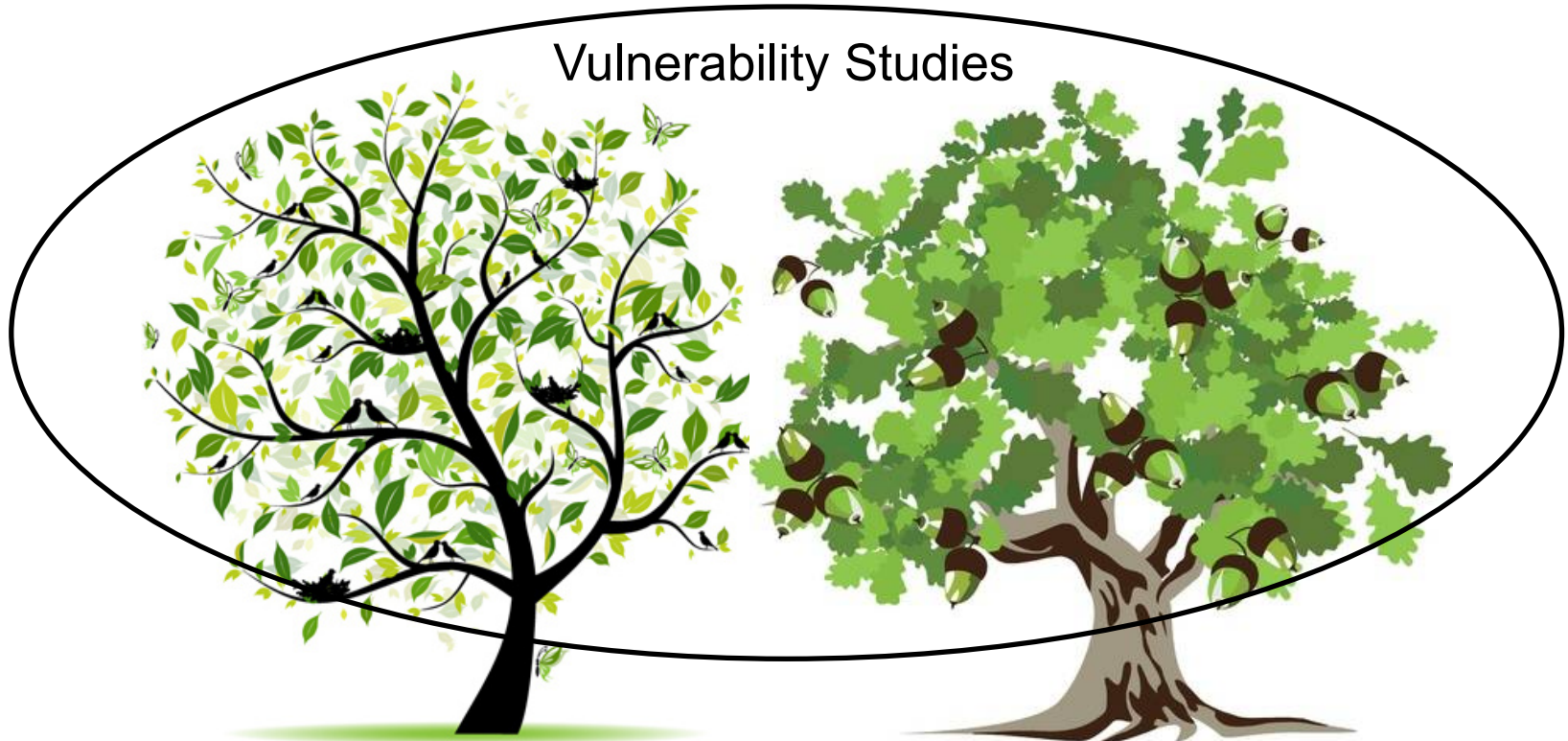
Domino Effect

**Catastrophic  
Damage**

A **small** failure  
"Trigger"



# Vulnerability Studies in the Two Fields



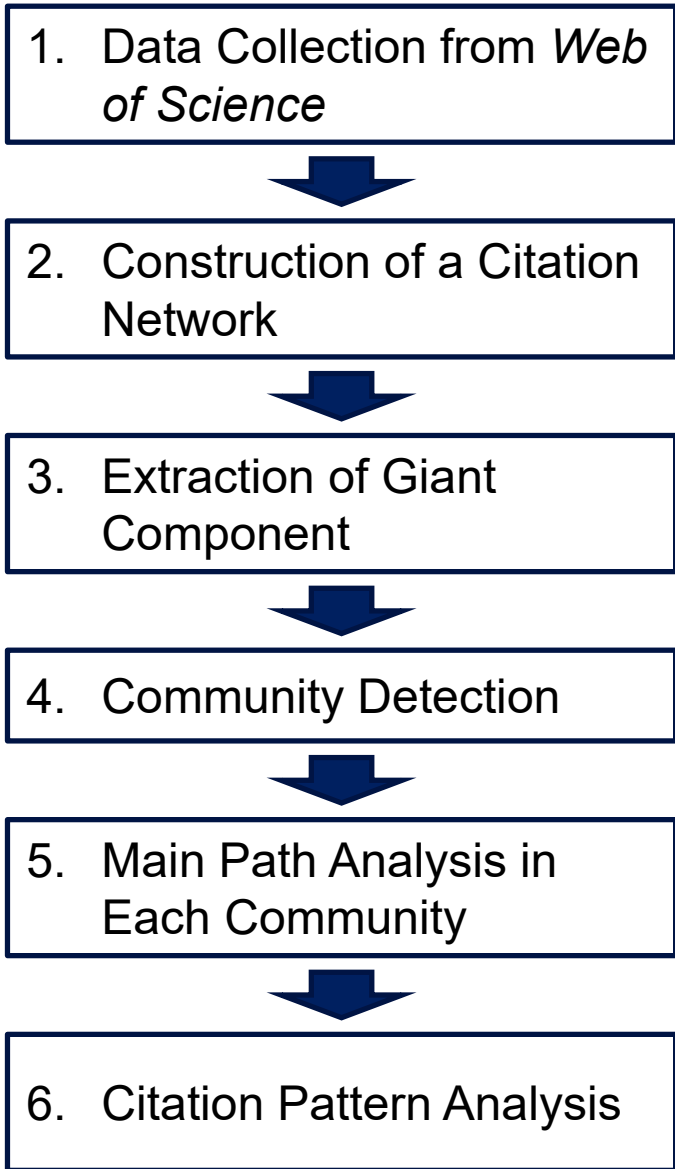
Roots

Transportation

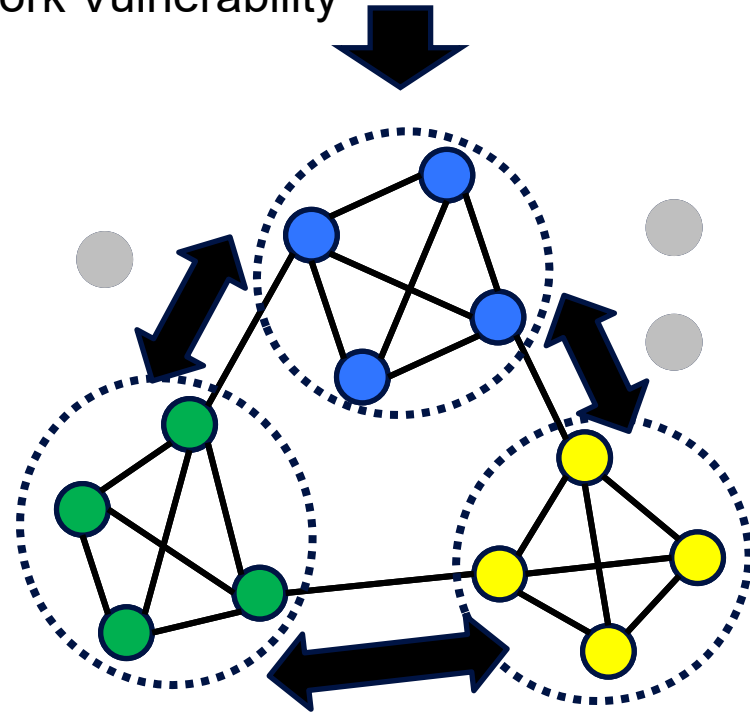
Complex Networks

- A large number of studies on network vulnerability have been published in the two fields
- How have these two fields evolved over time?
- How have these two fields influenced each other?

# Citation Network Analysis



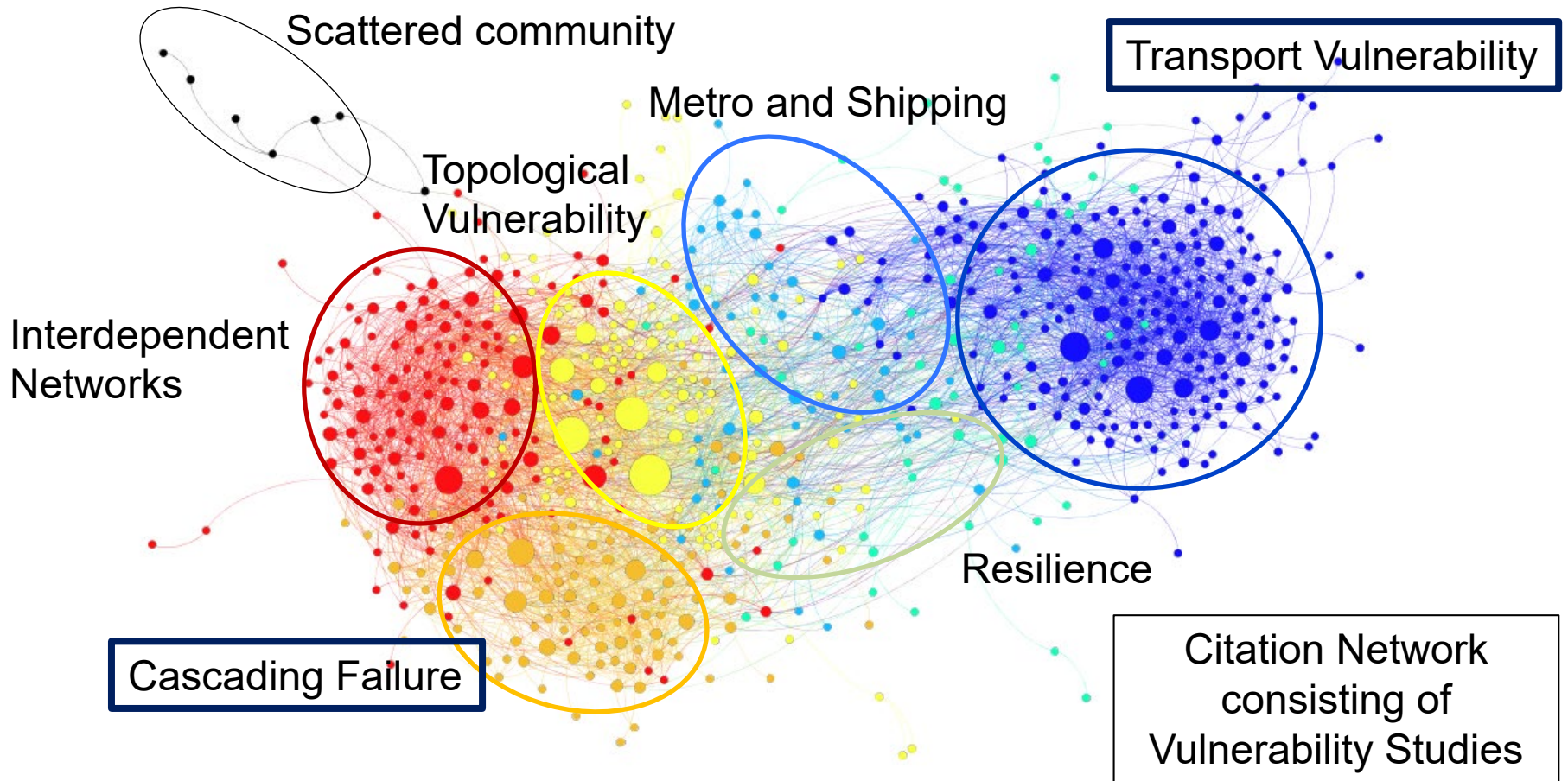
Network Vulnerability



Relations between Communities

# Community Structure in Citation Network

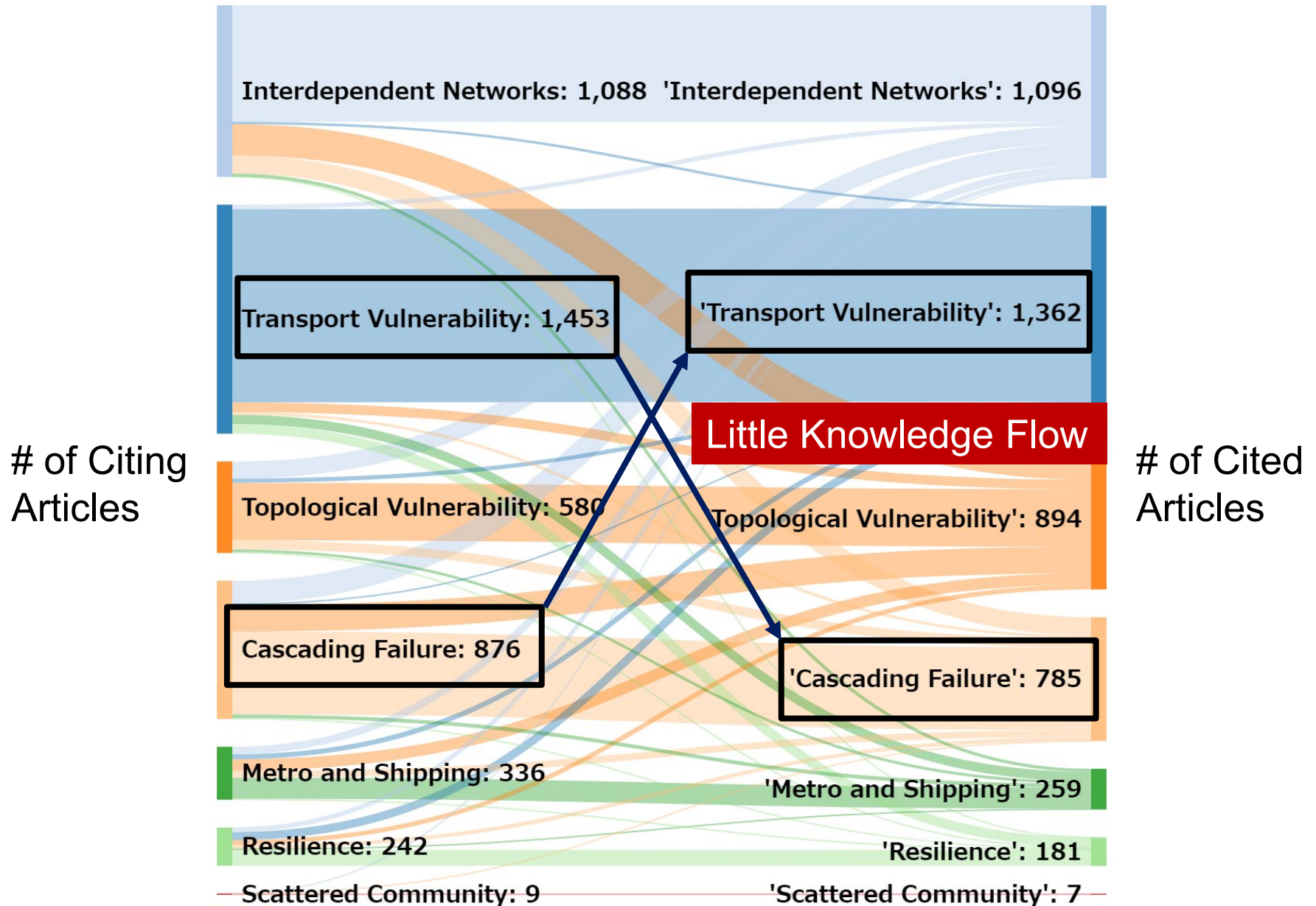
- Community structure of citation network has been identified



Paper in Preparation

Sugishita K. and Asakura Y., Citation Network Analysis of Vulnerability Studies in the Fields of Transportation and Complex Networks.

# Citation Pattern Analysis



# Gridlock as Cascading Failure

## Cascading Failure in Complex Networks



Blackout



Communication Disturbance



Financial Crisis

➔ Similar phenomenon occurs in Transportation Networks... **Gridlock**



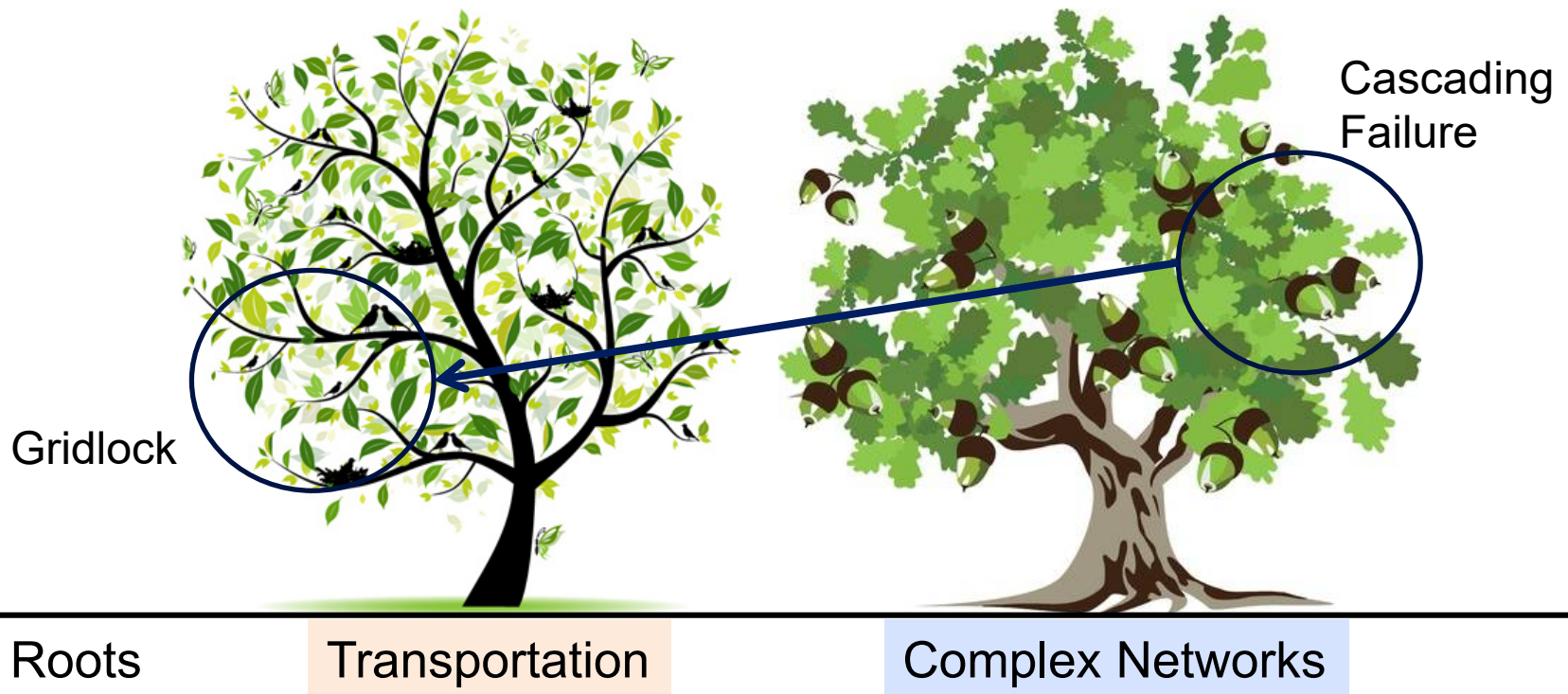
Gridlock

- Gridlock: Traffic completely standstills with zero/minimal flow (Mahmassani et al., 2013)
- Gridlock seldom occurs, but it brings about catastrophic damage



# Research Objectives

- This study aims
  1. To analyze gridlock in transportation networks from the perspective of cascading failure in complex networks
  2. To investigate influences of route choice behavior on vulnerability to cascading failure



◆ Assumptions in many studies about **cascading failure in complex networks**

- Flow is simply assigned on the shortest paths
- Flow is extremely fast (like electrical flow)
- Failures sweep over instantaneously and system suddenly collapses

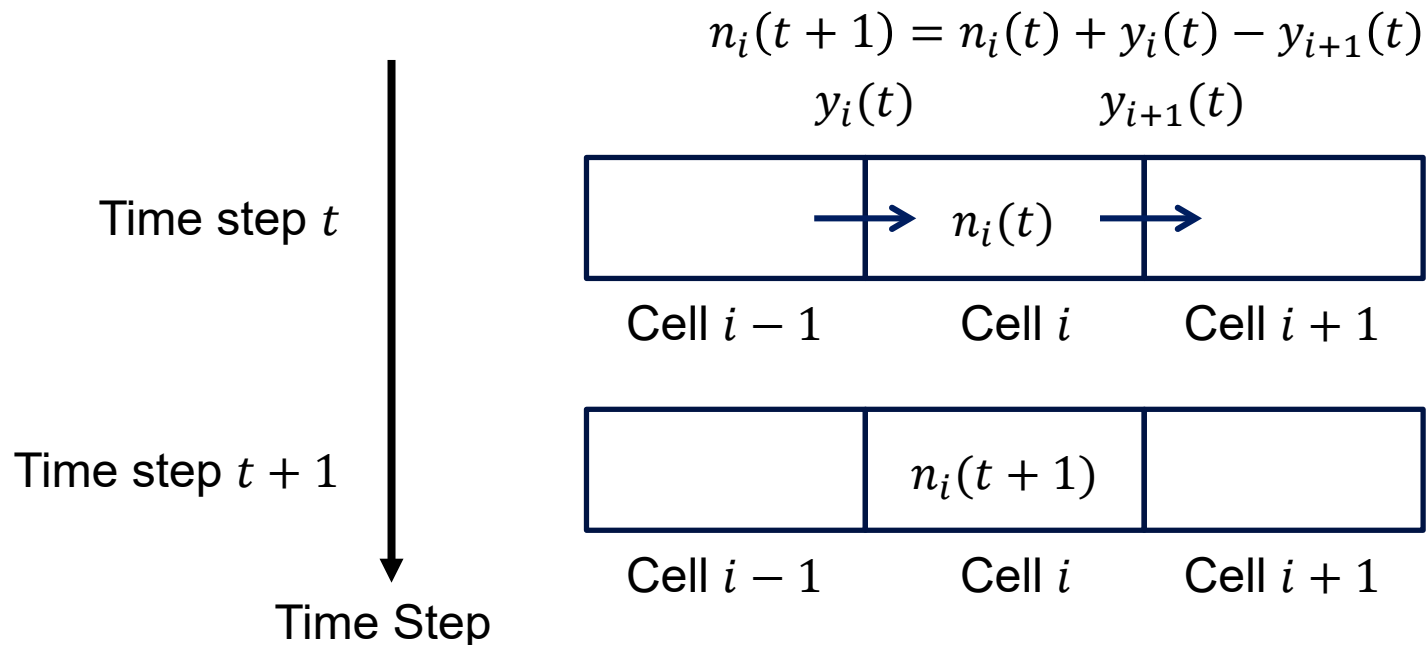


◆ Assumptions in this study about **gridlock in transportation networks**

- Flow is based on the **travelers' route choice behavior** (distinctive property in transportation networks)
- Flow is relatively slow (**propagation of shockwaves**)

# Cell Transmission Model (CTM)

- In order to consider properties of traffic flow, Cell Transmission Model (Daganzo, 1994; 1995) is utilized
- CTM captures **dynamic traffic phenomena** such as queue formation, shockwave propagation
- Time is discretized
- A network is represented as cells



- Following rules are satisfied for travelers' route choice behavior
  - a traveler who departs at time  $t$  can obtain information about travel time of all routes calculated by the network state at  $t - 1$
  - a traveler never change the route after departure
- Travelers choose their routes based on logit model

$$p_k^{rs}(t) = \exp(-\theta T_k^{rs}(t-1)) / \sum_{i \in P_{rs}(t)} \exp(-\theta T_i^{rs}(t-1))$$

$p_k^{rs}(t)$ : the choice probability of the  $k$ th route in the set of routes from  $r$  to  $s$

$\theta$ : the scale parameter

$T_k^{rs}(t)$ : the travel time of the  $k$ th route from  $r$  to  $s$  at time  $t$

$P_{rs}(t)$ : the set of all routes from  $r$  to  $s$  at time  $t$

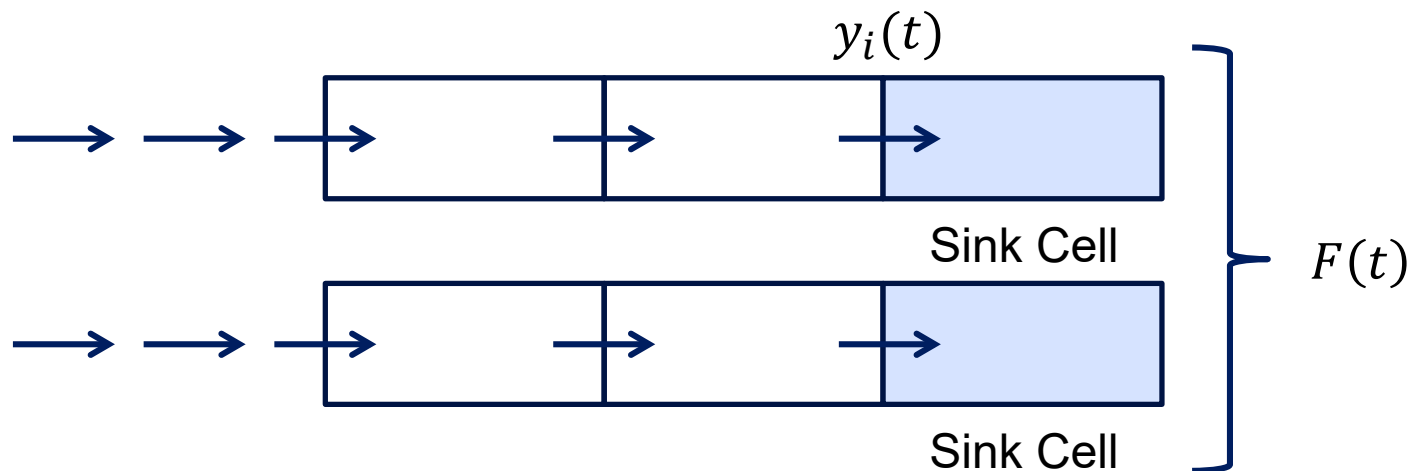
- We assess network throughput as the performance index

$$F(t) = \sum_{i \in C_{sink}} y_i(t)$$

$F(t)$ : the network throughput representing the amount of flow completing travel and exiting from the network in the time interval between  $t$  and  $t + 1$

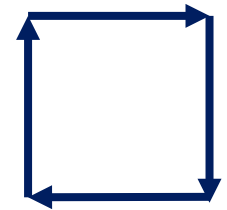
$y_i(t)$ : the inflow to cell  $i$  in the time interval between  $t$  and  $t + 1$

$C_{sink}$ : the set of all sink cells



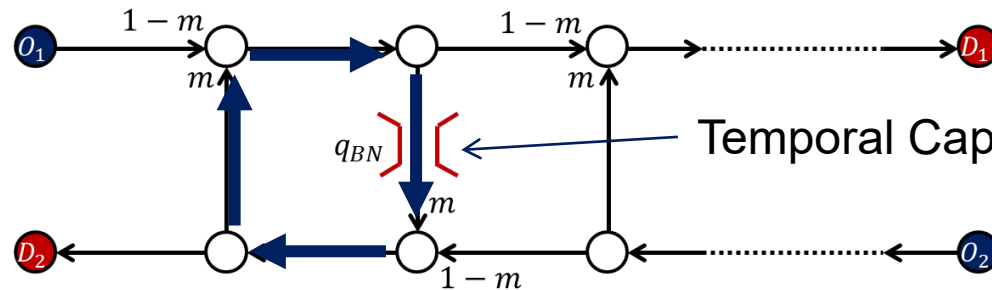
# Networks and Directed Cycles

- Investigate influences of route choice behavior in two networks
- Topology is slightly different
  - Network A has one directed cycle
  - Network B has two directed cycles (small and large)



Directed Cycle

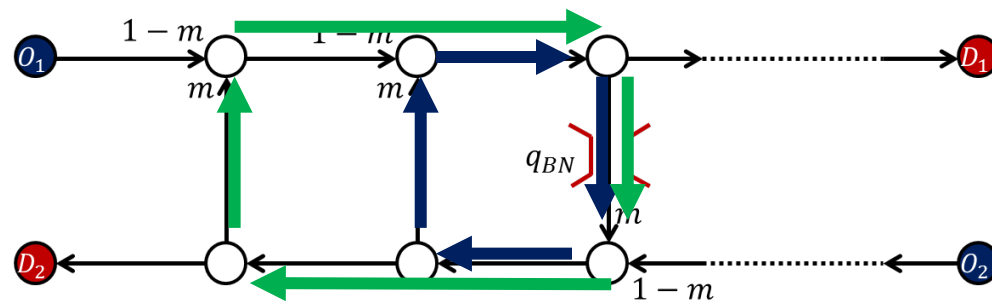
Network A



Temporal Capacity Reduction

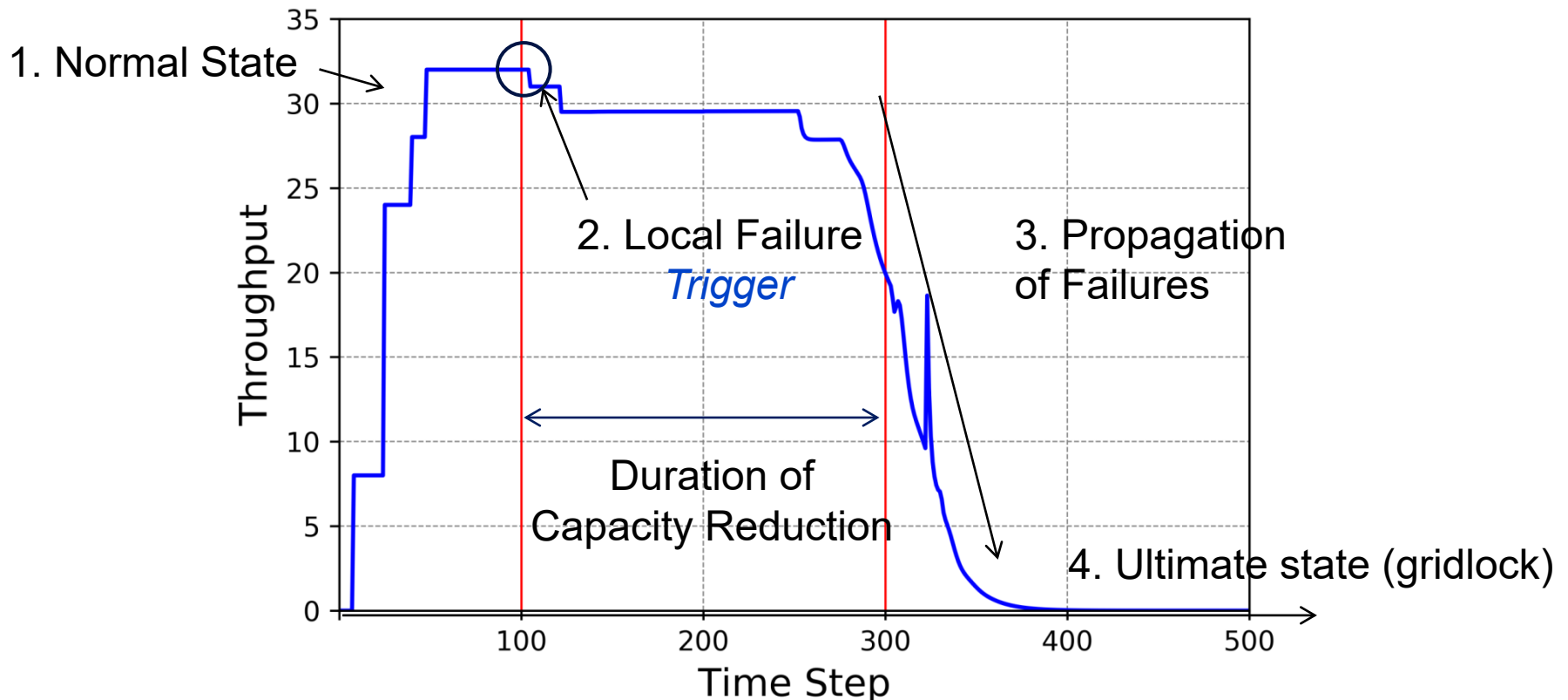
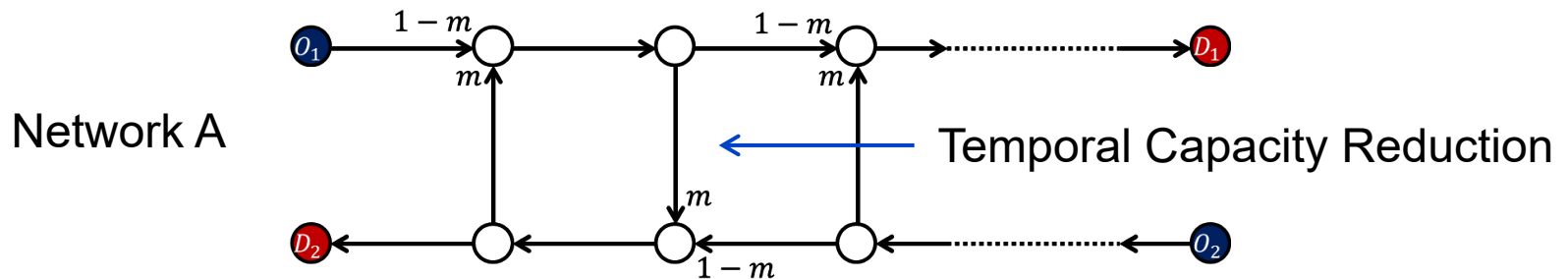
$m$ : Merging Ratio

Network B



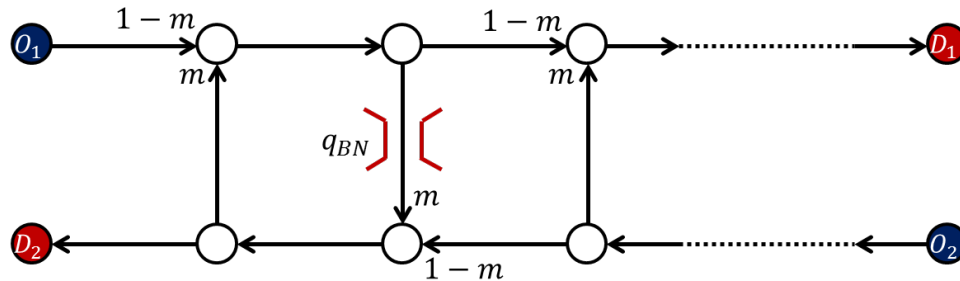
# Gridlock as Cascading Failure

- Gridlock can be captured as cascading failure

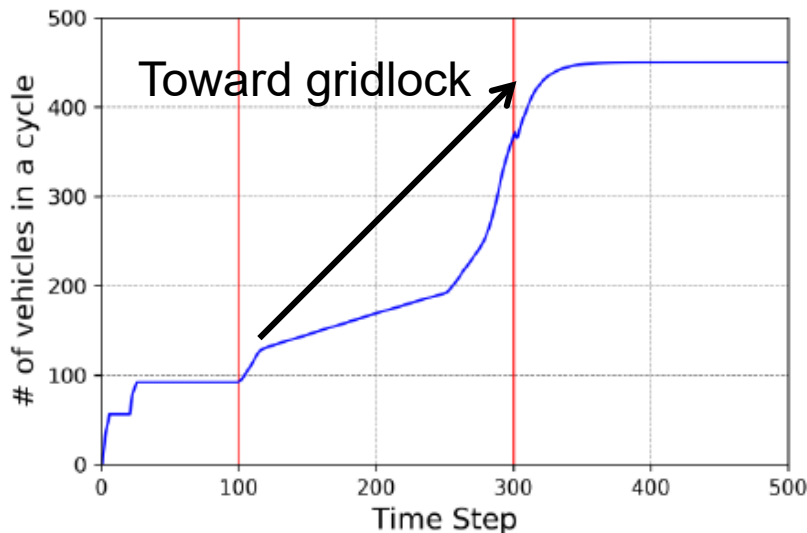


# Influence of Route Choice Behavior

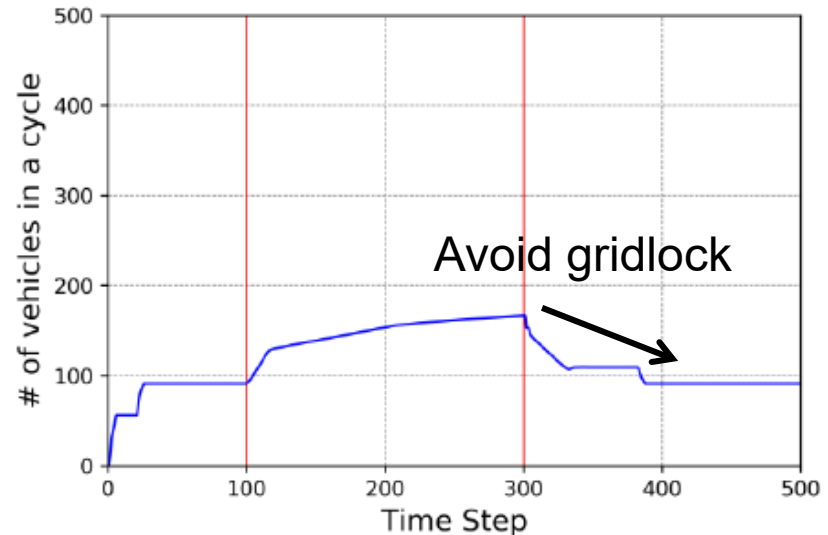
- Results indicate that route choice behavior with high sensitivity may help to avoid gridlock naturally



Network A



Scale parameter  $\theta = 0.001$   
(less sensitive)

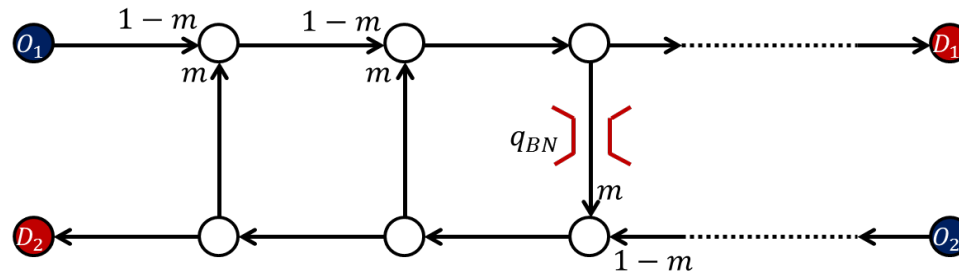


Scale parameter  $\theta = 0.01$   
(more sensitive)

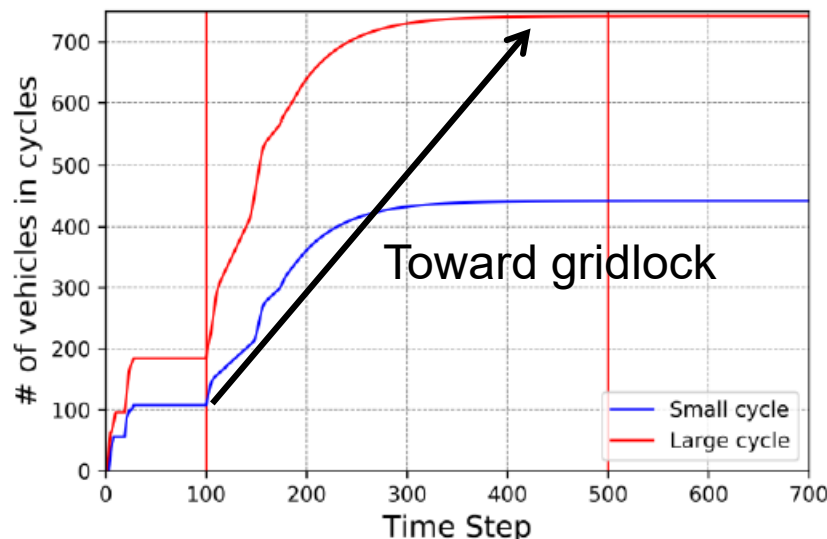


# Influence of Route Choice Behavior

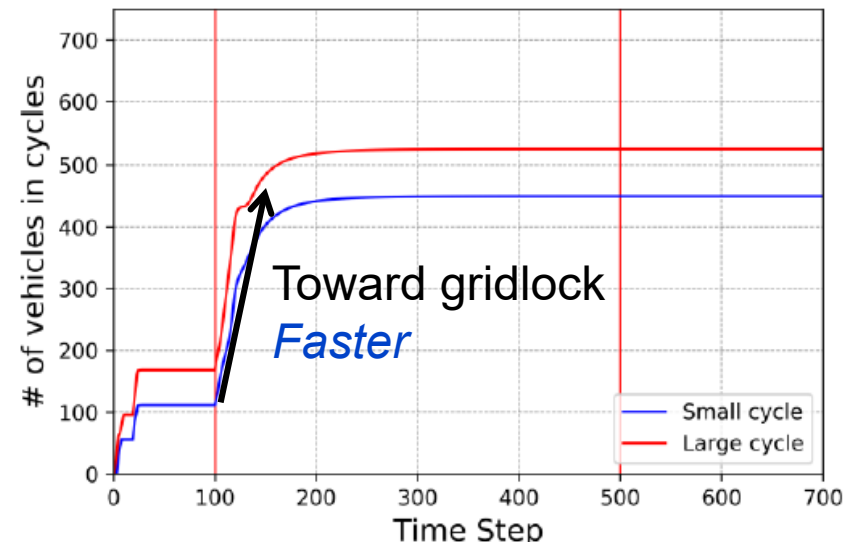
- However, gridlock state can be reached much faster due to sensitive route choice behavior



Network B



Scale parameter  $\theta = 0.0$   
(less sensitive)



Scale parameter  $\theta = 1.0$   
(more sensitive)

- ◆ Citation network analysis on vulnerability studies
  - Citation network consists of vulnerability studies in the fields of transportation and complex networks
  - Community structure is identified
  - Citation pattern analysis revealed that little knowledge flow between transport vulnerability and cascading failure
- ◆ Gridlock from perspective of cascading failure
  - Gridlock can be captured as cascading failure: 1) normal state, 2) small failure, 3) propagation of failures, and 4) ultimate state
  - Route choice behavior sometimes helps to avoid gridlock naturally, but at other times it worsens the situation toward gridlock much faster
  - In transportation networks, critical points can be identified as directed cycles with overloaded demand

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Thank you very much!