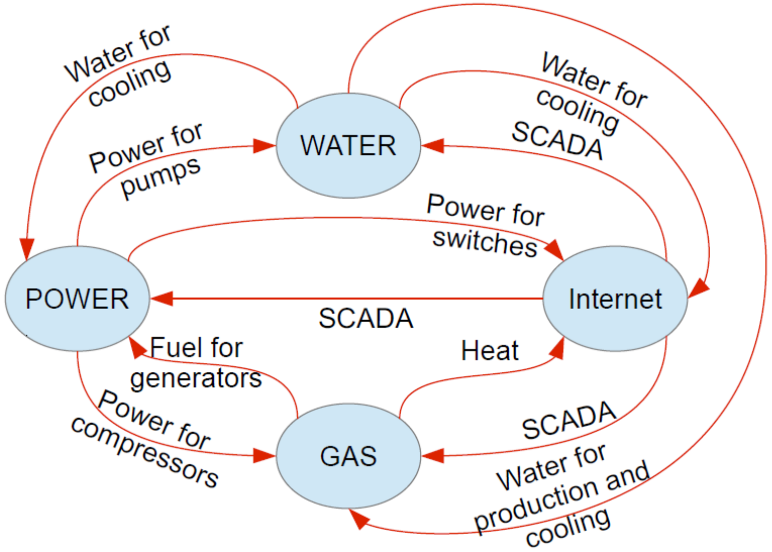
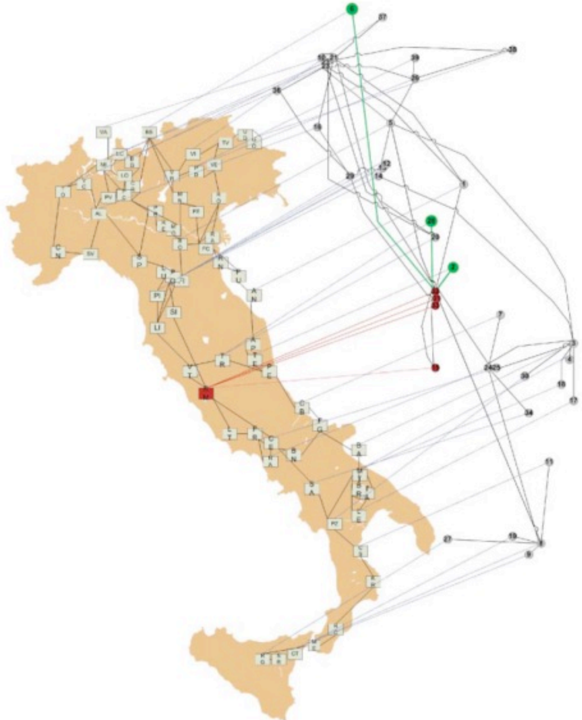
Introduction to project topics
for the course of
Performance of Computer Networks

Novella Bartolini

Damage assessment and recovery after network failures

Massive network failures in networks may derive from single failures





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Failure of nodes in one network causes failure of nodes in a second network

Supervisory Control And Data Acquisition (SCADA systems) cause interdependency

communication network – other infrastructures

Structural heterogeneity

Different behaviors of propagation

Problem Setting

Supply Graph *G*

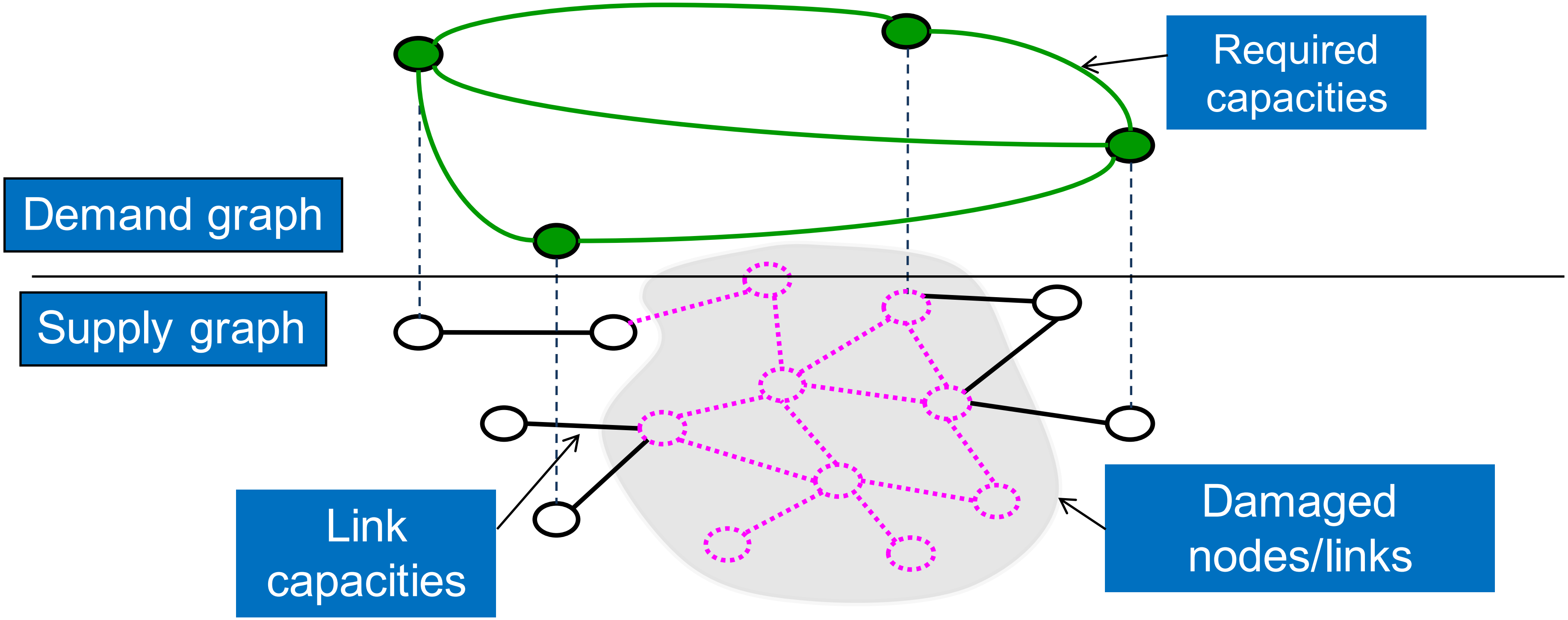
- Damaged communications network

Demand Graph *H*

- Flows with required capacity for mission critical applications

Goal

- Make lowest cost repairs (restorations) in *G* to serve <u>all</u> flows in *H*



Network failures

Network management under failures

- Analysis and design (models of failure propagation, network engineering)
- Assessment (monitoring and network tomography)
- Recovery (algorithms for service restoration)

Related funded projects and collaborations:

ARL (Army Research Lab)

DTRA (Defense and Threat Reduction Agency)

Collaborations with Penn State University and IBM

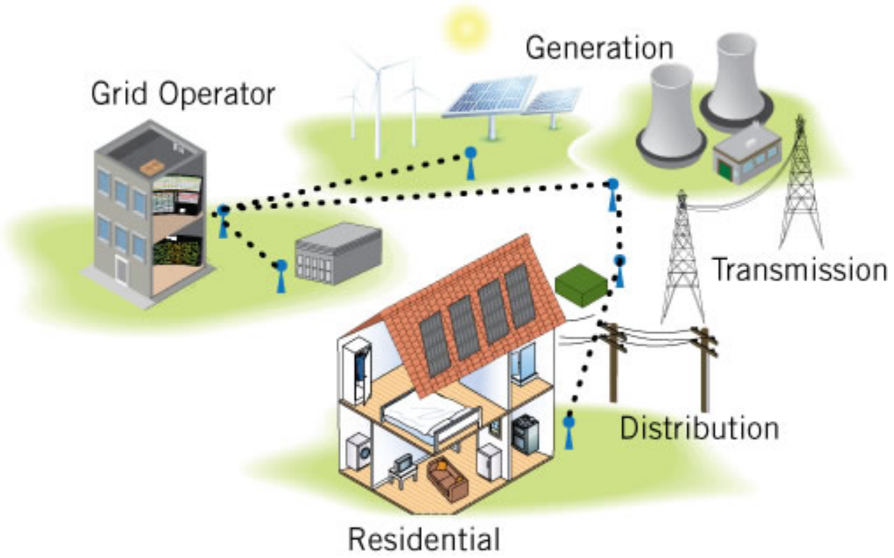
Cascading failures

[1] H. Khamfroush, N. Bartolini, T. La Porta, A. Swami, J. Dillman,
On Propagation of Phenomena in Interdependent Networks,
in *IEEE Transactions on Network Science and Engineering*, Vol. 3, n. 4, July 2016.

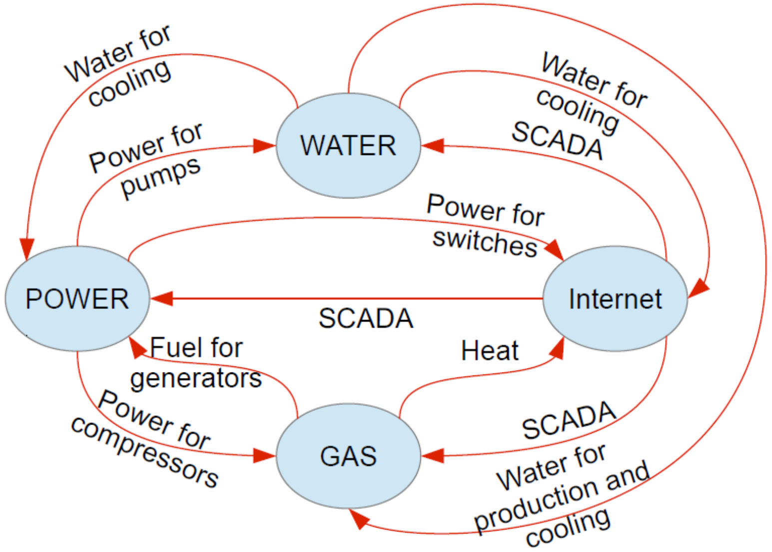
Large scale interdependent networks

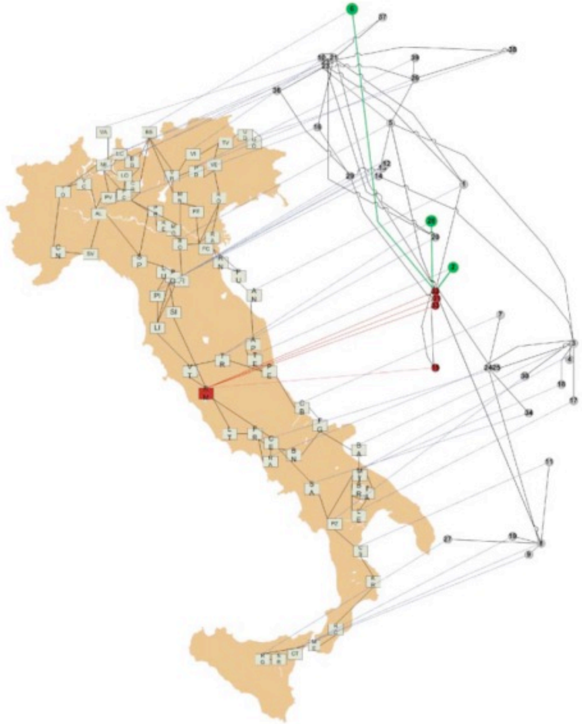
- Interdependent networks: functionality or performance of one network depends on the other

Internet controls power grid &
grid provides power for the Internet



Massive network failures in networks





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Failure of nodes in one network causes failure of nodes in a second network

Supervisory Control And Data Acquisition (SCADA systems) cause interdependency

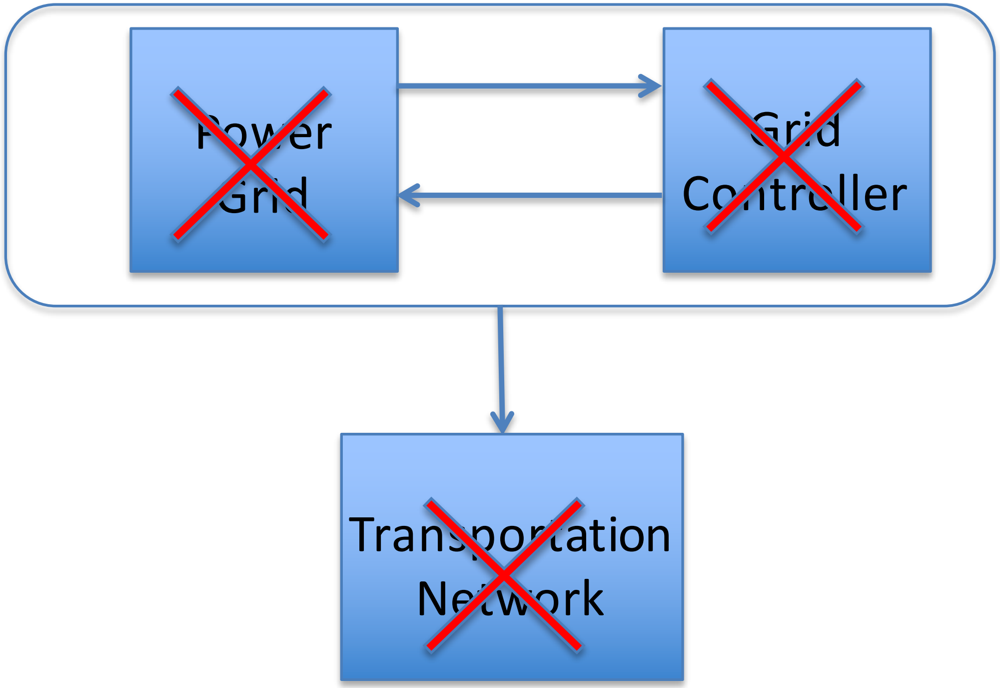
communication network – other infrastructures

Structural heterogeneity

Different behaviors of propagation

Motivation

- Blackout in Italy, Sep 2003 : Power outage affected all Italy
- 56 million people have been affected

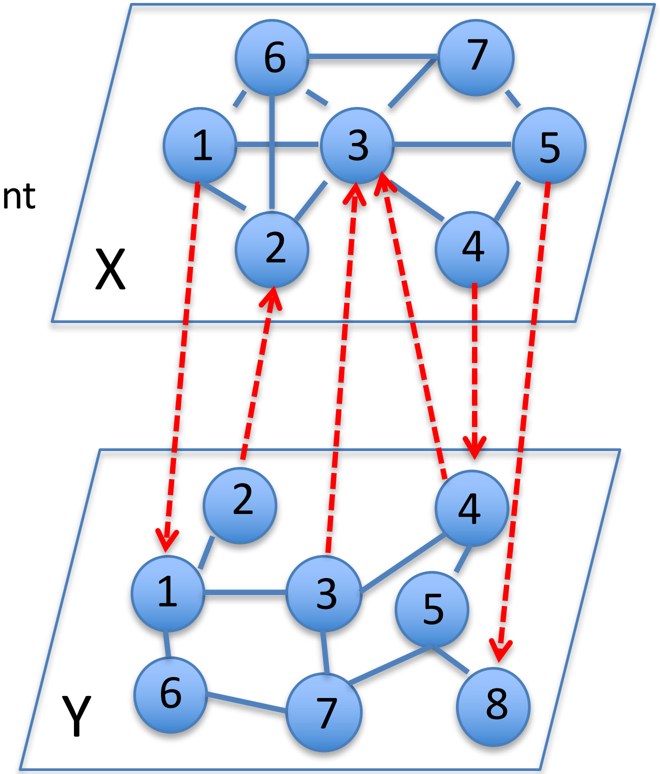


Cascading failures

- Two inter-dependent networks X and Y with respectively, n_x and n_y nodes
  - Red links represent inter-connectivity and blue links represent intra-connectivity links
- Given the initial spreaders set
  - Calculate the probability of transition into a new state
  - Expected time to full spread or end of the propagation

Example: For node *3* of network *X*

- Set of intra-connection ={1,2,3,5,6,7} of *X*
- Set of inter-connection={3,4} of *Y*



Problem 1: characterize the propagation, control the speed of propagation

Problem 2: design robust networks (with failure detection capability and slow propagation)

Network tomography

[1] Ting He, Novella Bartolini, Hana Khamfroush, InJung Kim, Liang Ma, Tom La Porta,
Service Placement for Detecting and Localizing Failures Using End-to-End Observations,
in *Proceedings of the 36th IEEE International Conference on Distributed Computing Systems (IEEE ICDCS 2016)*

[2] N. Bartolini, T. He, H. Khamfroush,
Fundamental Limits of Failure Identifiability by Boolean Network Tomography,
in *IEEE Proceedings of the International Conference on Computer Communications (IEEE INFOCOM 2017)*

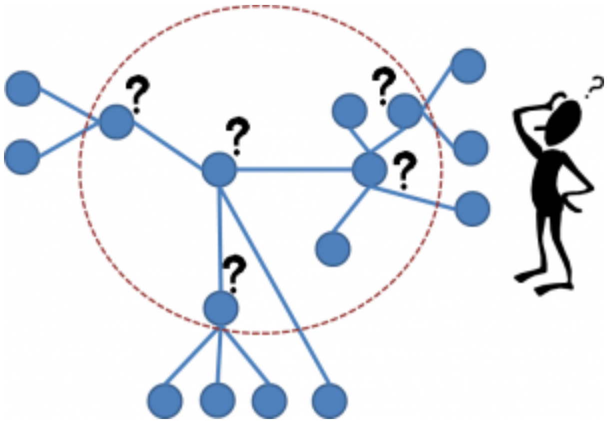
Network tomography

Network Tomography:
Inferring internal network state through external, end-to-end measurements

Relevance

Knowledge of the network state is important

- Prompt intervention after failure
- Efficient Routing
- Resource Allocation
- Balancing network loads
- QoS measurement: service degradation



Challenges

Large and costly overheads due to active probing

Problem 1: Optimal monitor placement for detecting and localizing failures

Problem 2: Minimize number of monitoring paths

Problem 3: Maximize identifiability of failures

Problem 4: Design new network topologies with maximum identifiability of failures

Sensor and actuator networks

(drones + terrestrial robots + sensor networks)

Related funded projects:

NATO Science for Peace and Security G4936,
Hybrid Sensor Networks for Emergency Critical Scenarios
(2015-2018, in collaboration with GJU and MS&T)

PSU seed project,
Digital innovation in food security using a 28,000 farmer living lab in Kenya

Monitoring drones

Sensors can be mounted on drones.
In this case they are typically complex sensing devices interfaced with artificial intelligence for image processing, event recognition.

Why a network and not a single drone doing all the work?

Amatrice – Italy (2016)

Why a network and not a single drone doing all the work?

In the aftermath of a catastrophe, drones are used to find people, provide medicines to inaccessible and possibly unknown locations.

> The intervention must be fast, as it may save lives.
>
> The battery of the drone, especially with payload, ensures a limited flight time.

Better to use multiple coordinated drones, which autonomously spread through the area.

Why a network and not a single drone doing all the work?

- The use of a squad in inaccessible terrains is also motivated by the limited supplies available on site

Examples:

low/high temperatures (imagine you are monitoring a glacier),

absence of roads,

absence of connectivity…

Current work on Sensor and Actuator Networks

Field crops at Penn State

Current work on Sensor and Actuator Networks

Farms in the Philippines

Current work on Sensor and Actuator Networks

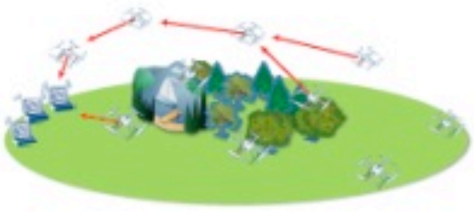
Farms in Uganda

Current work on Sensor and Actuator Networks

(a) Launch

(b) Autonomous deployment

(c) Anomaly detection



(d) Transmission to sink

(e) Task assignment

(f) Task execution

Research challenges

- Different concept of coverage to be optimized! Dynamic coverage: a point is covered if it is traversed, or if it is explored. There may be deadlines.

- Flight at different heigths cause different sensing capabilities. The propeller wings cause noise in the measurements. Height

- Battery limitations are rigid, you can recharge the device but you cannot let it drop!

-> Analytical formulation of optimization problems, algorithmic solutions

Boolean Network Tomography

N. Bartolini, A. Massini, et al.
Fundamental Limits of Failure Identifiability by Boolean Network Tomography,

Outline

- Motivation
- Network Tomography
- Definitions
- Problem Formulation
- General Network Monitoring Bounds
- Service Network Monitoring Bounds
- Performance Evaluation

Motivation

- Identifying the state of network nodes is beneficial for many functions in network management
  - Performance analysis
  - Route selection
  - Network recovery

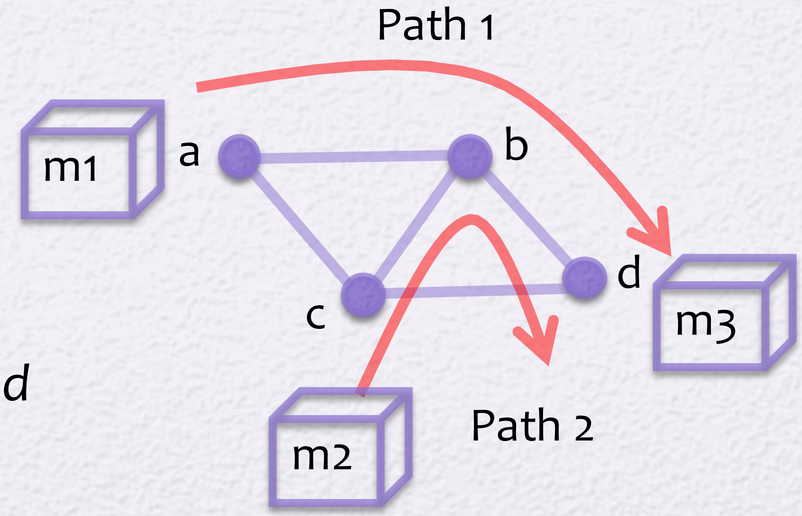
- Direct measurement is not always available due to large traffic overhead, access control, etc.

- Built-in monitoring may fail detecting failures caused by misconfigured/unanticipated interactions between network layers (silent failures)

One solution: Network Tomography

Boolean Network Tomography (BNT)

- Diagnose the health of network elements from the health of end-to-end communications perceived between measurement points
- Node states can be measured indirectly via monitoring paths



Path 1 & path 2 fail: can't localize
Path1 fails, path 2 working: link ab failed

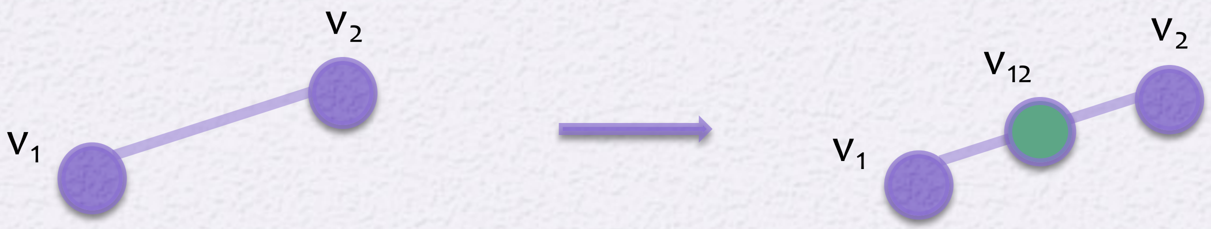
Our Problem Setup

- Network is modeled as undirected graph $G=(V,E)$, V representing nodes and E representing links
- Failure set, i.e. set of failed nodes: $F \subseteq V$
- Total number of nodes: n
- Nodes states can be measured indirectly only by monitoring paths
- Set of monitoring paths: $P=\{p1,p2,\ldots,pm\}$
- The state of a path is normal if all traversed nodes are in normal state

Our Problem Setup

- Failure set, i.e. set of failed nodes: $F \subseteq V$

  Notice that we focus on the failure of nodes only, as links can be modeled as virtual nodes.



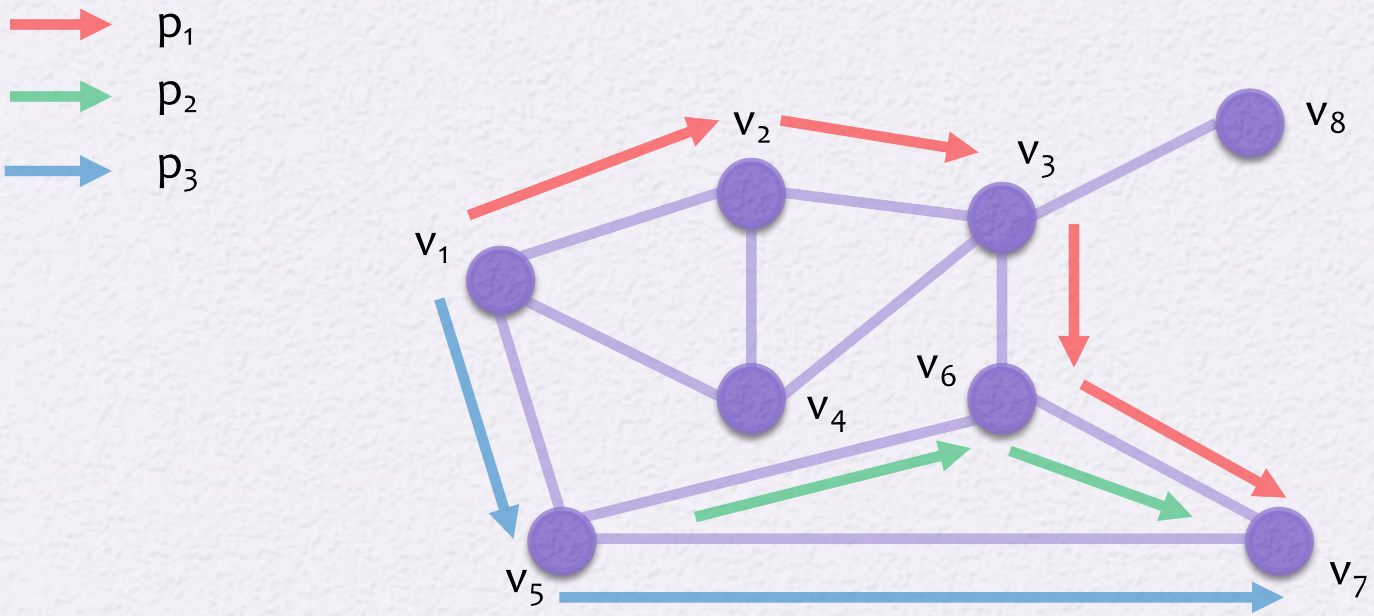
Node v_{12} represents the status of link (v_1, v_2)

Our Problem Setup

- Incident set of v_i : set of paths affected by the failure of node v_i noted by P_{v_i}
- Incident set of paths of a failure set *F:* $P_F \triangleq \cup_{v_i \in F} P_{v_i}$
- Test matrix T is an $m \times n$ matrix, where $T|_{i,j} = 1$

  if $v_j \in p_i$ and zero otherwise
- The *j-th* column of T denoted with $b(v_j) \triangleq T|_{*,j}$ is the characteristic vector of P_{v_j} and called binary encoding of v_j

Test matrix T



$$T = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \end{bmatrix}$$

Identifiability Definition

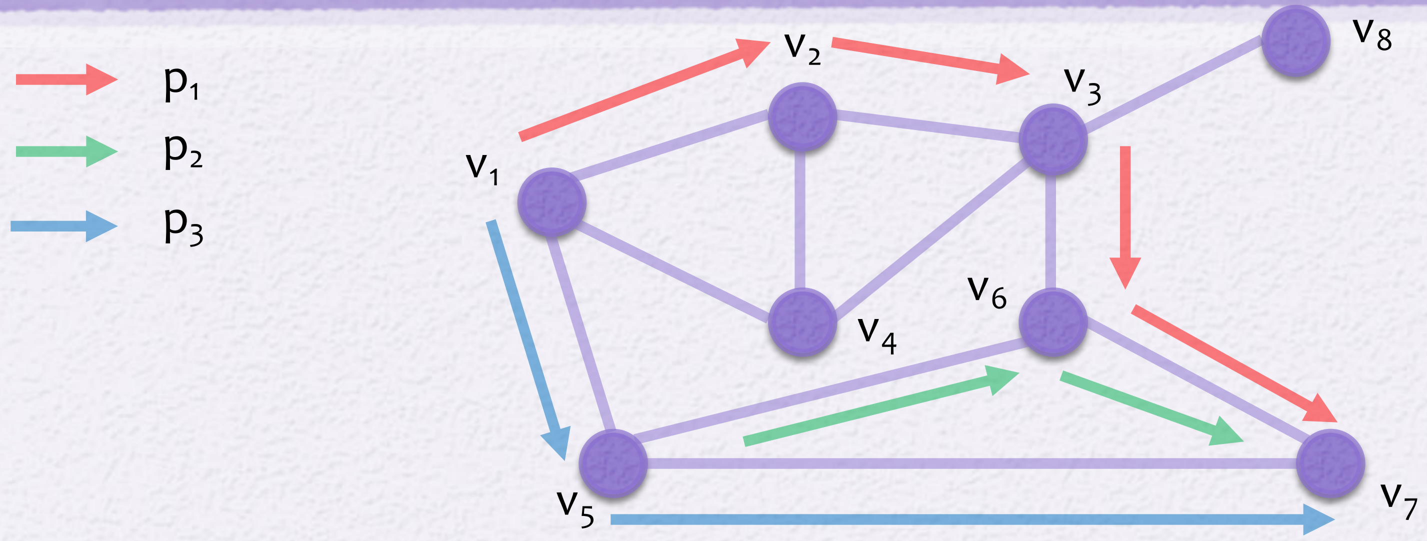
Definition *Given a set of monitoring paths* P *and a node* $v_j \in V$, v_j *is* k-identifiable *with respect to (wrt)* P *if for any failure sets* F_1 *and* F_2 *such that* $F_1 \cap \{v_j\} \neq F_2 \cap \{v_j\}$, *and* $|F_i| \leq k$ *(*$i \in \{1, 2\}$*),*

$$\bigvee_{v_i \in F_1} b(v_i) \neq \bigvee_{v_z \in F_2} b(v_z)$$

where with "$\bigvee$*" we refer to the element-wise logical* OR.

Definition *A node* v_i *is 1-identifiable wrt* P *if and only if* $b(v_i) \neq \mathbf{0}$, *and* $\forall v_j \neq v_i$, $b(v_j) \neq b(v_i)$, *i.e., its binary encoding is not null and not identical with that of any other node.*

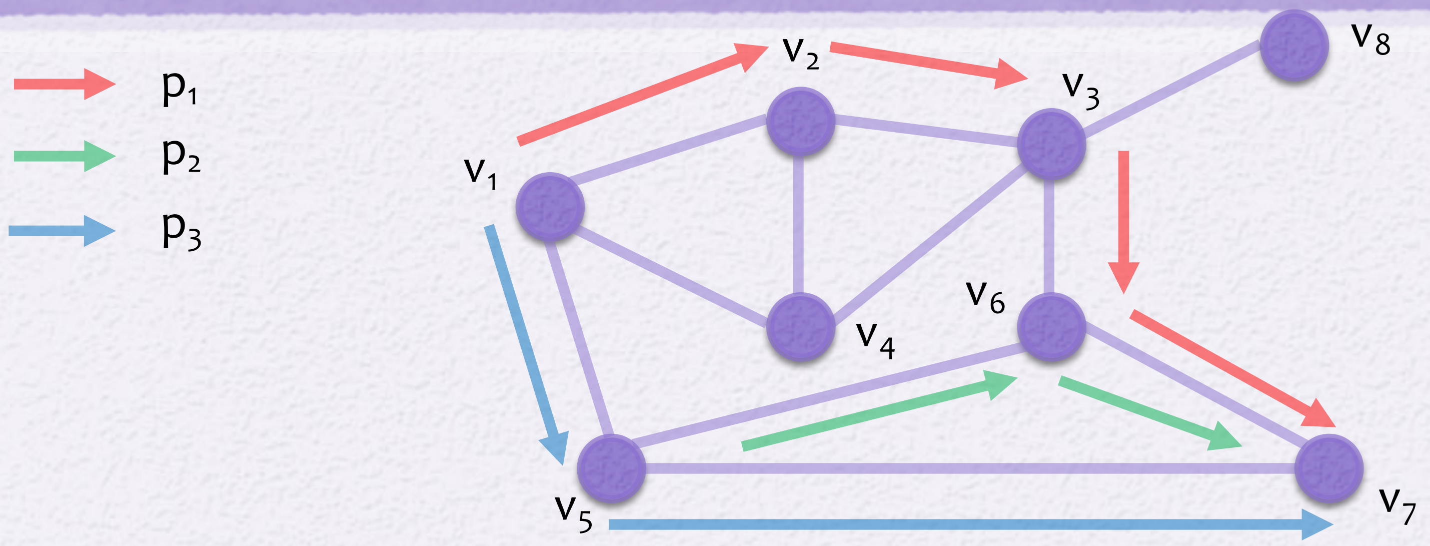
Test matrix T



$$T = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \end{bmatrix}$$

Which nodes are 1-identifiable?

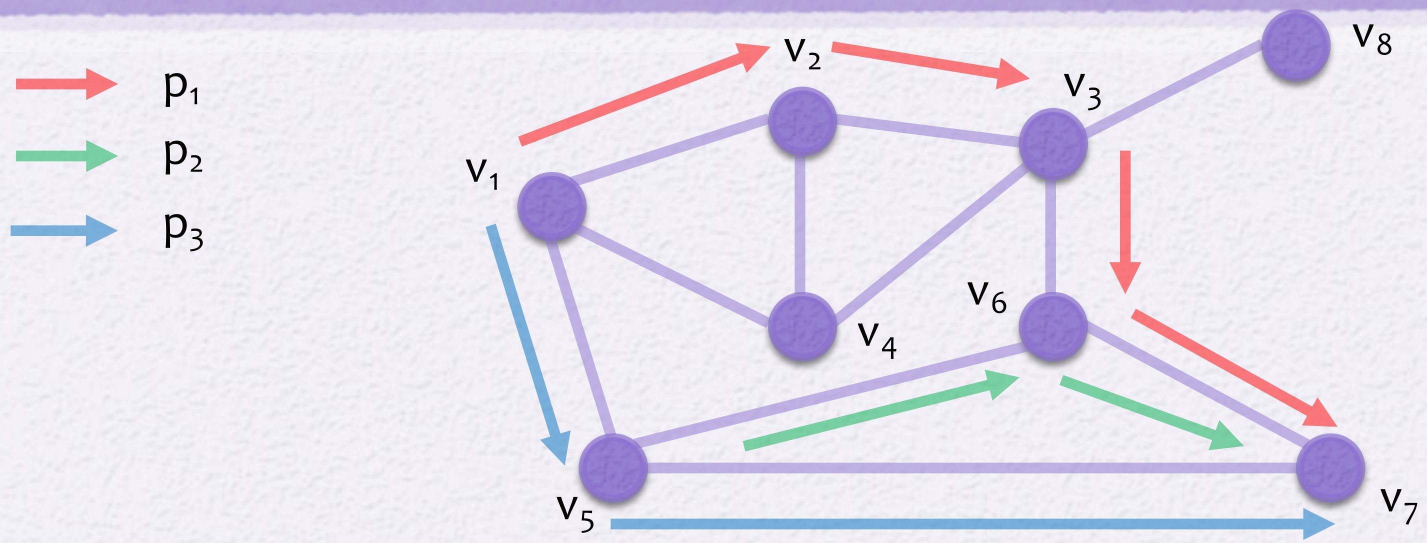
Test matrix T



$$T = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \end{bmatrix}$$

Which nodes are 1-identifiable? v_1, v_5, v_6, v_7

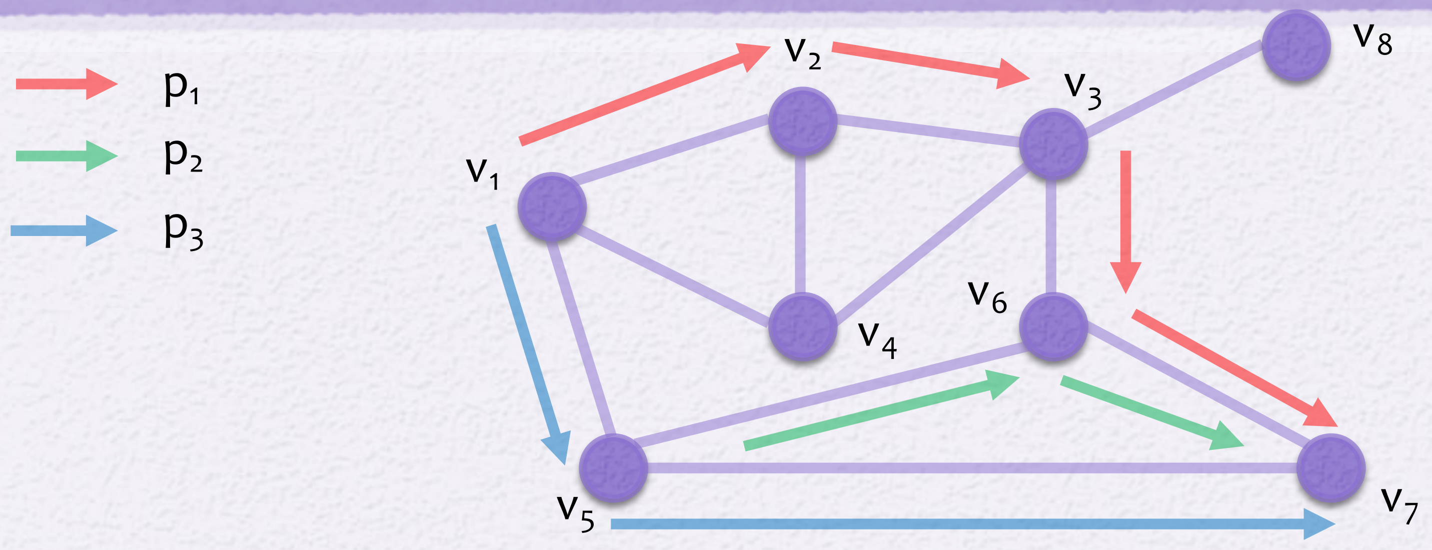
Test matrix T



$$T = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \end{bmatrix}$$

Why is v_4 not identifiable?

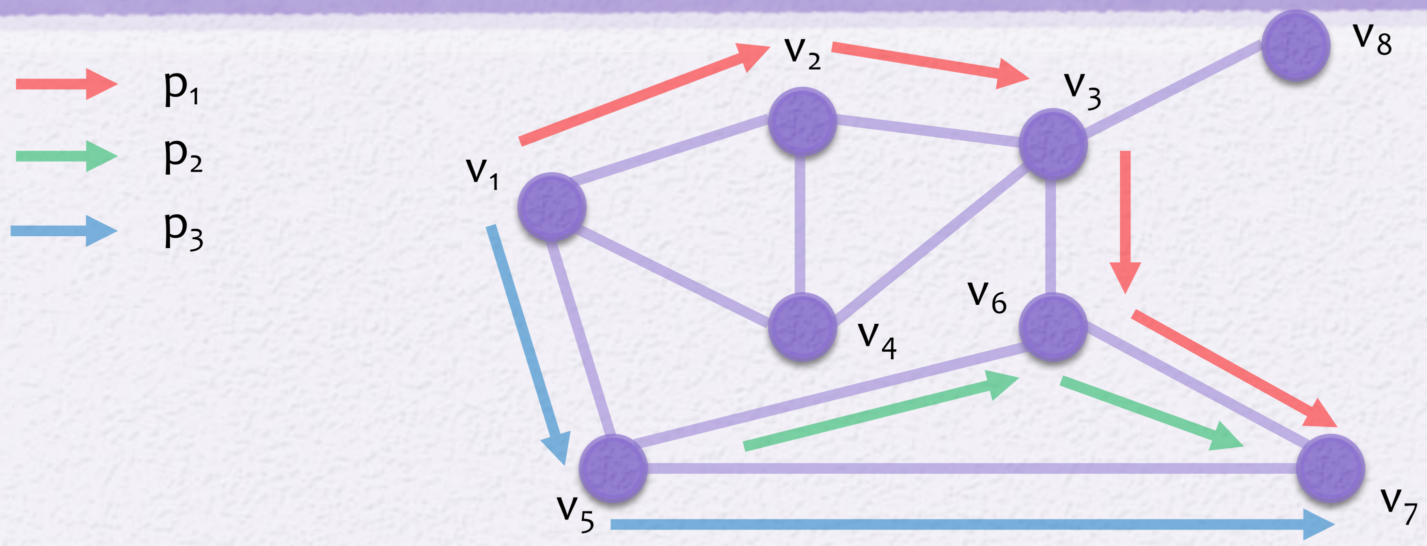
Test matrix T



$$T = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \end{bmatrix}$$

Why is v_4 not identifiable?
It is not even traversed by any path! Same as v_8.

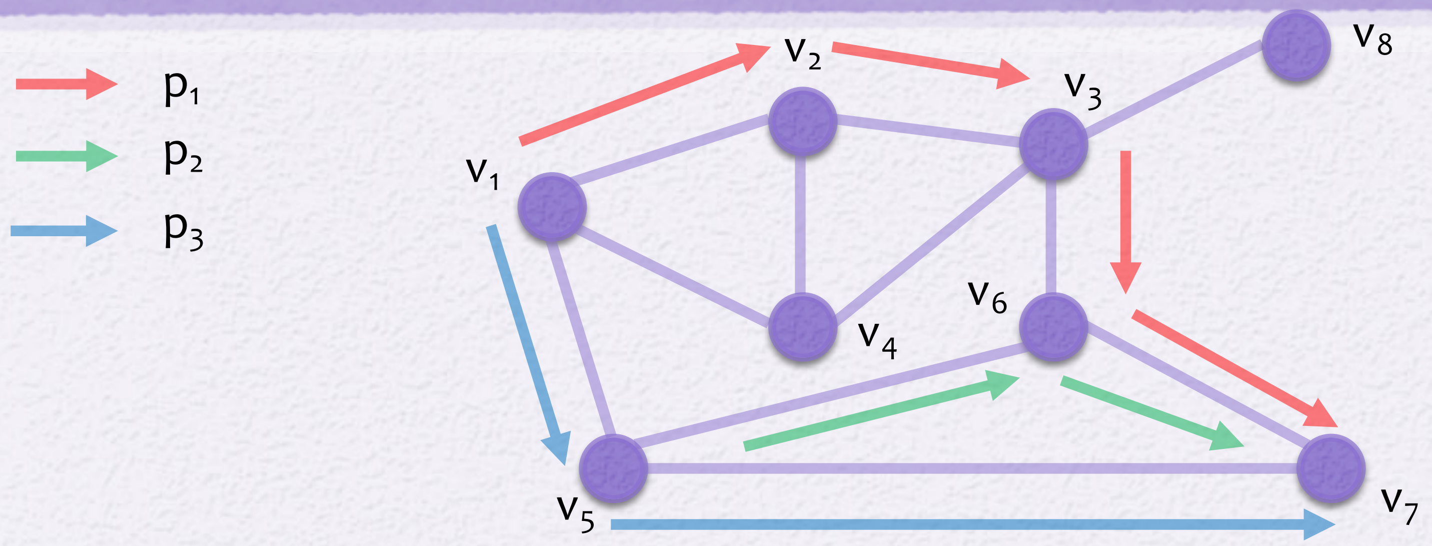
Test matrix T



$$T = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \end{bmatrix}$$

Why are v_2 and v_3 not identifiable?

Test matrix T

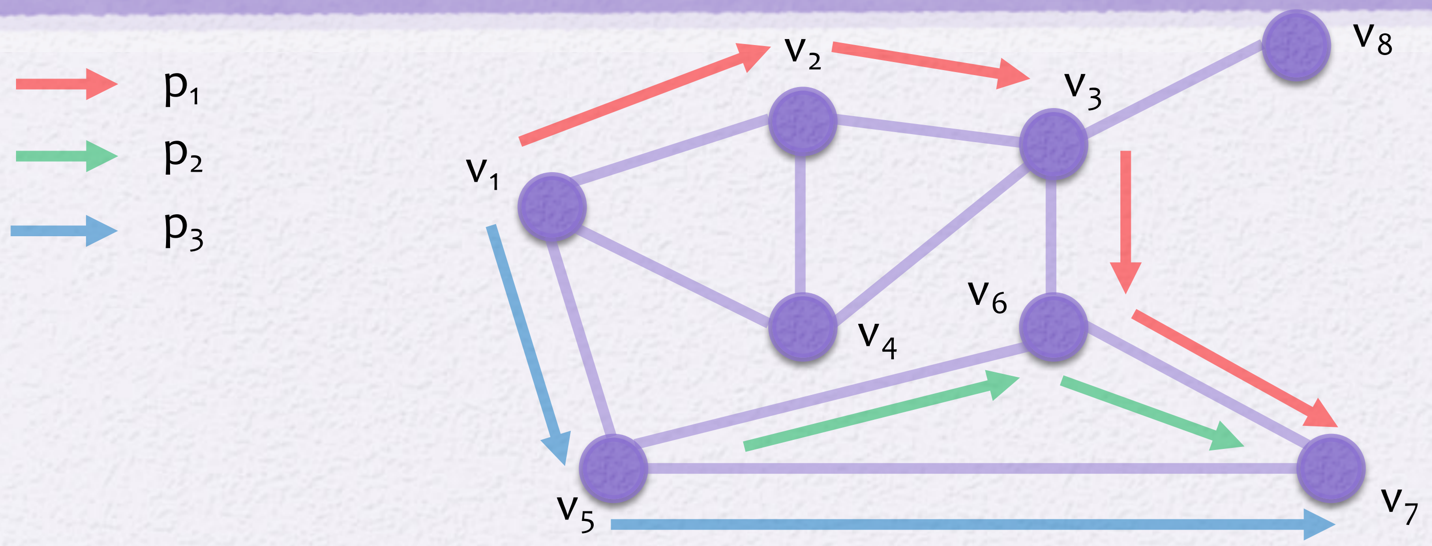


$$T = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \end{bmatrix}$$

Why are v_2 and v_3 not identifiable?

They have the same Boolean encoding! Whatever failure occurs, we cannot distinguish v_2 from v_3.

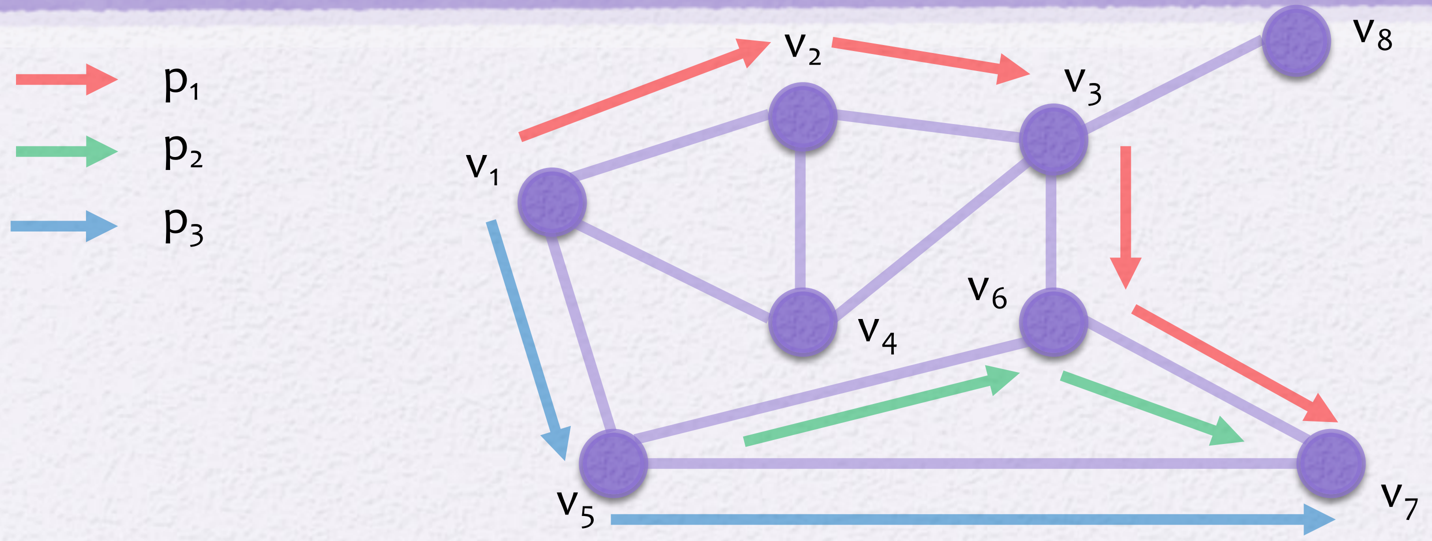
Test matrix T



$$T = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \end{bmatrix}$$

Which nodes are 2-identifiable?

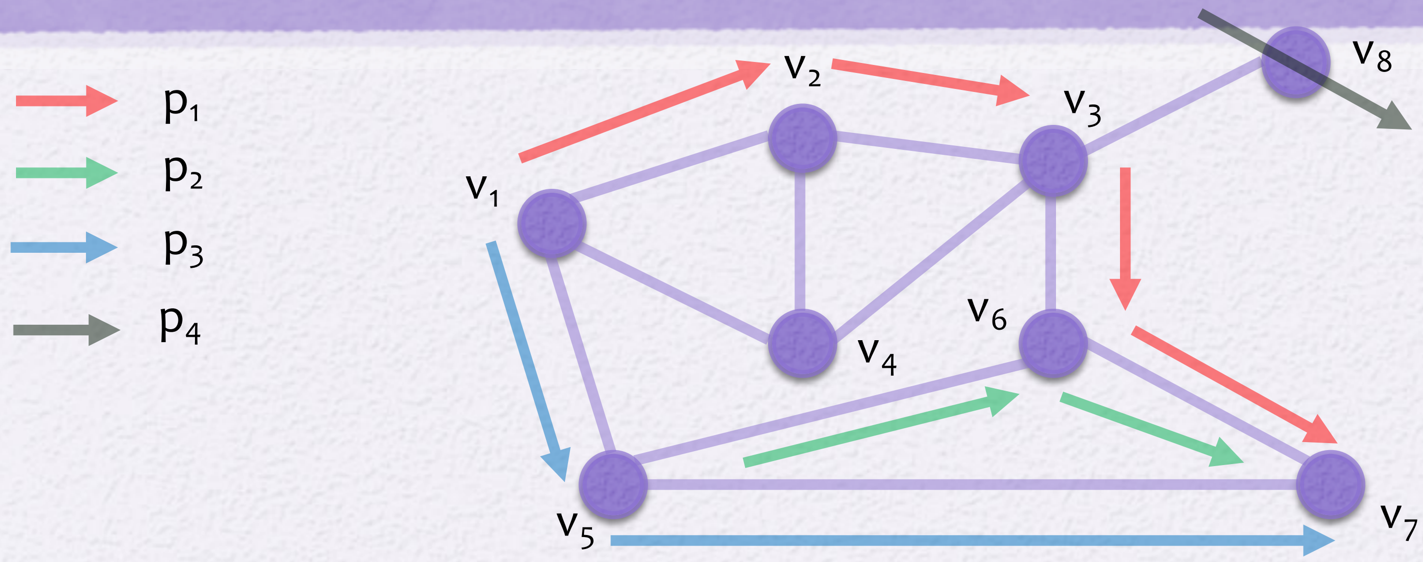
Test matrix T



$$T = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \end{bmatrix}$$

Which nodes are 2-identifiable? None of them!

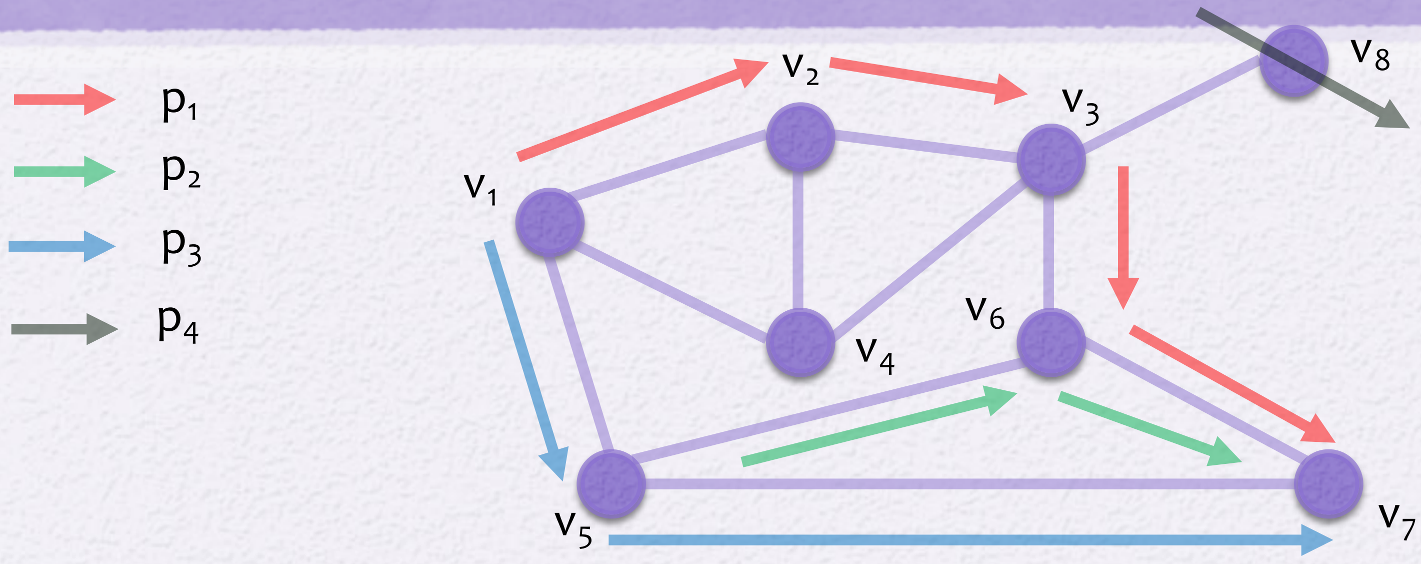
Test matrix T



$$T = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Which nodes are 2-identifiable?

Test matrix T



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Which nodes are 2-identifiable? v_8