U.S. Army Research, Development and Engineering Command

Risk and Resilience Controllability-Observability in Cloud Security

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

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Outline

- Cloud computing vulnerabilities, and risk factor
- Developing metrics for quantifying risk and resilience in cloud computing
  - Determining asset dependency and criticality, criticality surface
  - Modeling with multi-disciplinary approaches (e.g., control theory, time Petri net, Bayesian network)
- Controllability and Observability
- An example for identifying critical nodes and controllability

Cloud, Risk, and Metrics

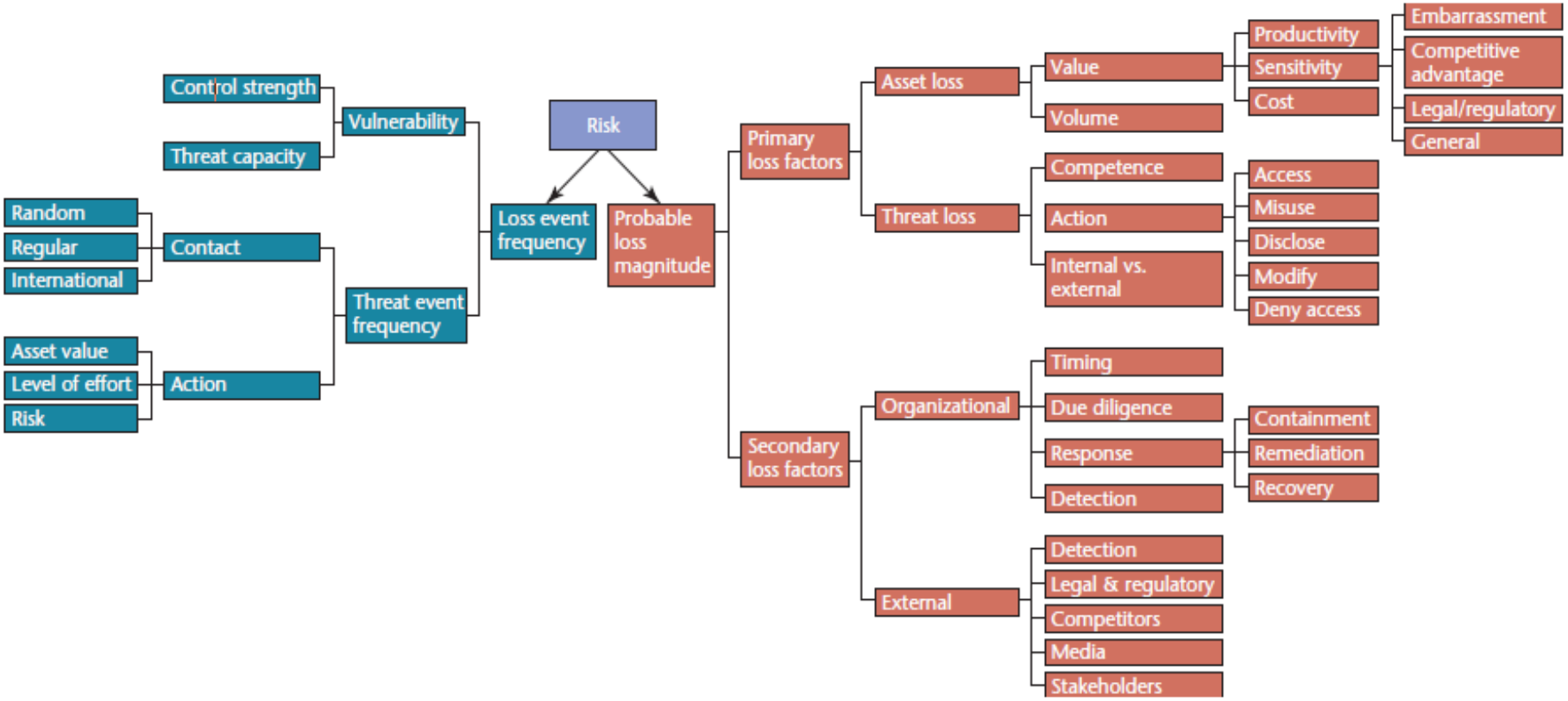
- Cloud computing security requires defense at both server and client sides
  - Some subsystems of cloud are not controlled by cloud subscribing organizations
- Metrics are needed to measure and verify the correct functioning of a subsystem and effectiveness of security controls
- How does cloud computing affect the models and metrics development on risk, resilience, and criticality surface?

Risk Factors in Cloud Computing

- ISO 27005 defines risk as “the potential that a given threat will exploit vulnerabilities of an asset or group of assets and threby cause harm to the organization”
- Risk management assesses risk and aims at reducing to an acceptable level
- How does cloud computing affect risk factors?
  - Risk factors
    - The likelihood of a harmful event (or loss event frequency as per ISO 27005)
    - The consequence of an harmful event

Risk Taxonomy

Factors contributing to risk according to the Open Group's risk taxonomy*



- What are cloud computing influence on risk factors from both customer and service provider perspectives?

* www.opengroup.org/onlinepubs/9699919899/toc.pdf

Source: B. Grobauer, T. Walloschek, and E. Stocker, "Understanding Cloud Computing Vulnerabilities," IEEE Security and Privacy, March/April 2011

Problem Statement

- Given incomplete information on vulnerabilities, threats, attacks, fully/partially compromised nodes, topology, types of hosts and servers over a cloud system (e.g., hybrid cloud, private cloud, public cloud, community cloud),

  determine how to accurately and efficiently

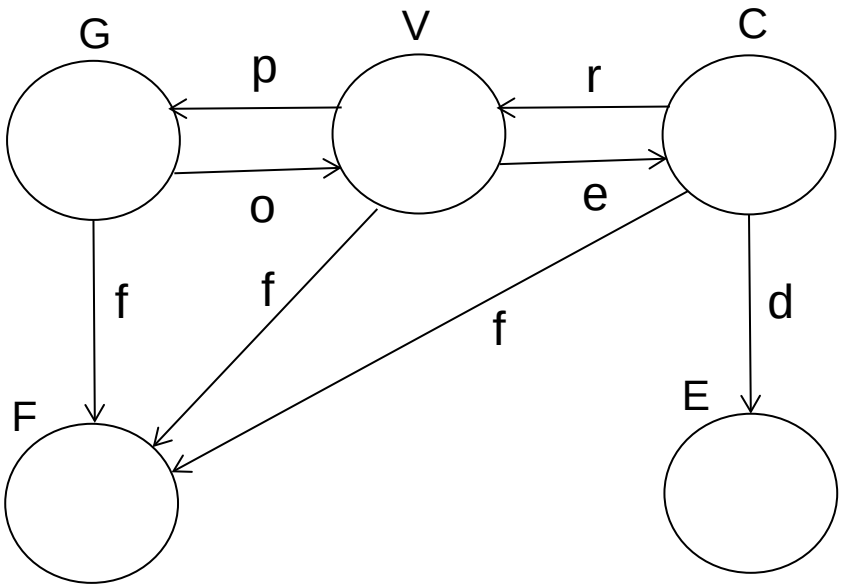
  – Assess dynamically the risk and resilience of the system,

  – Steer the system with some compromised nodes towards a system without compromised nodes by

    - Implementing recovery and resilience operations on the partially/fully compromised nodes or assets,
    - Strengthening resilience of the system

An Example of Cyber-Physical System

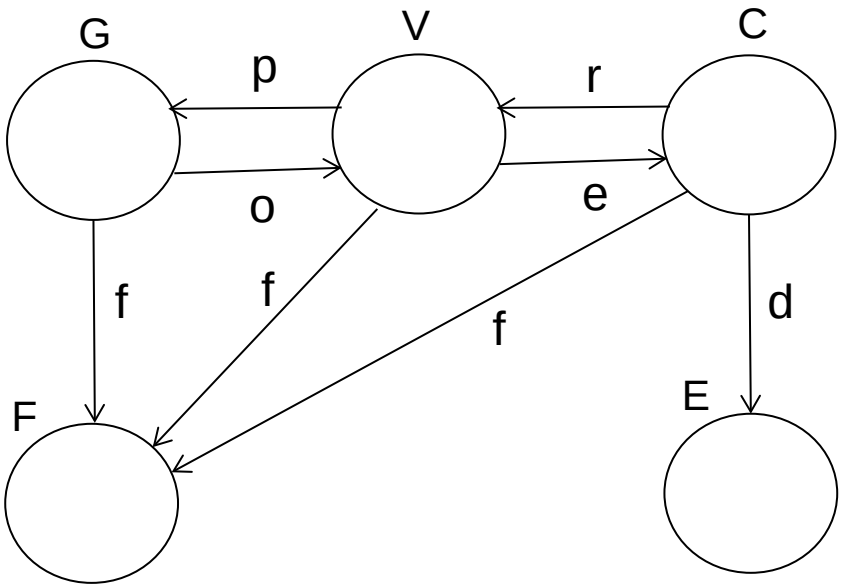
- Consider a network of *N* nodes/clients that are served by a cloud, where N = C+E+F+G+V and
  - G(t) denote the number of those nodes that do not have any known vulnerability at time *t*
  - V(t) denote the number of those nodes that have some known vulnerabilities at time *t,* but are not exploited yet
  - C(t) denote the number of those nodes that are compromised partially/fully through the exploitation of their vulnerabilities
  - E(t) denote the number of those nodes that are evicted due to that they cannot be recovered
  - F(t) denote the number of those nodes that have failed and do not operate due to physical failures
  - We can control the states and operation of nodes by r(t) and p(t).
  - We can measure C(t) and V(t)



- o: vulnerability occurance rate
- p: vulnerability patching rate
- e: vulnerability exploitability rate
- r : recovery rate
- d: cyber compromised-node eviction rate
- f: physical failure rate

An Example of Cyber-Physical System (cont'd)

- The dynamics of the system can be described by the following differential system
  - dG/dt = pV – oG – fG
  - dV/dt = oG +rC– pV-eV – fV
  - dC/dt = eV – rC –dE-fC
  - dE/dt = dC
  - dF/dt = f(G+V+C)
  - u(t) = (r(t), p(t))
  - y(t) = (C(t), V(t))



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Linear Time-Invariant System

- A dynamical system like a cloud system can be modeled as a linear time-invariant dynamic system

$$d\mathbf{x}(t)/dt = A\,\mathbf{x}(t) + B\,\mathbf{u}(t)$$

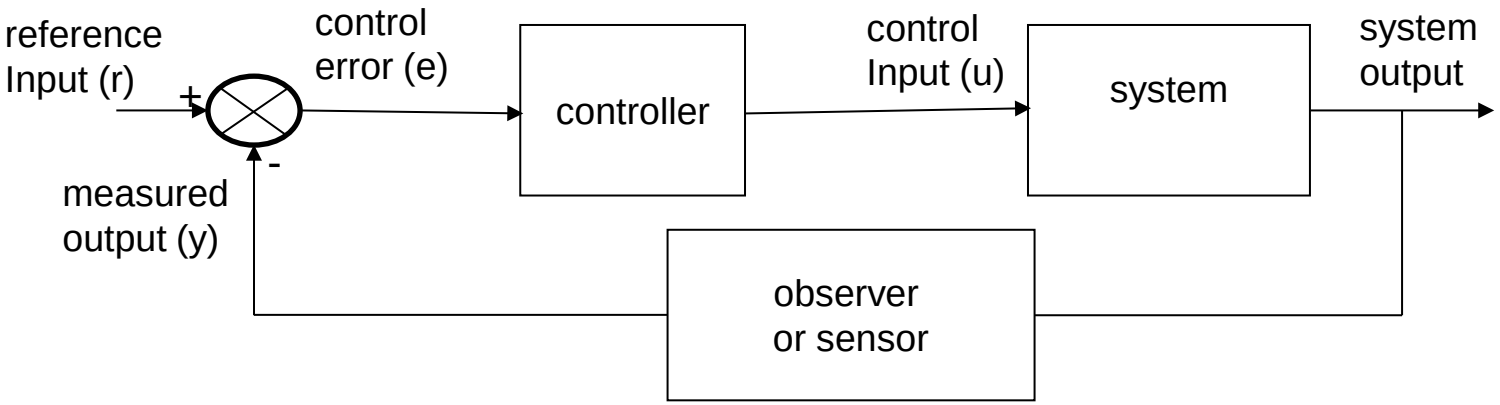
$$y(t) = C\,\mathbf{x}(t)$$

where

- the vector $\mathbf{x}(t) = (x_1(t), \ldots, x_N(t))^T$ captures the state of a network with *N* nodes at time *t*.
- The N x N matrix *A* describes the network's connectivity and interaction strength between nodes.
- The N x M input matrix *B* identifies the nodes controlled by a time-dependent input vector $\mathbf{u}(t) = (u_1(t), \ldots, u_M(t))^T$ controlled by an outside controller, where (M <= N)

Control-Theory for Cloud System

- Control-theory offers a powerful mechanism
  - to deal with disturbances, unpredictable changes, and uncertainties
  - to model, analyze, and design resource control and feedback systems



- Controller aims to maintain the difference between the reference input (e.g., performance targets as desired values) and the measured output (e.g., measured performance metrics), in spite of disturbance, noise, or attack that are not under control

Controllability and Observability

- **Controllability** is related to the ability of forcing the system into a particular state by using an appropriate control signal
  - A system is <u>controllable</u> if it can be driven in a desired direction, so that it will perform according to the specifications when inputs change
  - If the N x NM controllability matrix (B, AB, A^2B, …, $A^{N-1}B$) has full rank (i.e., rank N), then the system is controllable, according to Kallman's controllability rank condition
- **Observability** is related to the possibility of observing states of a system via output measurements
  - The state equation is <u>observable</u> if for any input state x_0 and for any input signal *u*, finite the output y sequence determines uniquely x_0
  - The pair (A,C) or the system is observable if the observability matrix has full rank N.

$$\begin{bmatrix} C \\ CA \\ \dots \\ CA^{N-1} \end{bmatrix}$$

LTI System with Noise and Attacker's Input

- Attacker's input u_a, process noise w_p, and measurement noise w_m can be added to a linear time-invariant dynamic system

$$d\mathbf{x}(t)/dt = A\,\mathbf{x}(t) + B\,\mathbf{u}(t) + u_a(t) + w_p(t)$$

$$y(t) = C\,\mathbf{x}(t) + B\,\mathbf{u}(t) + w_m(t)$$

Challenges on Implementing Observability

- A system is called **observable** if its complete internal state can be reconstructed from its outputs
- **Question:** Is it possible to measure (simultaneously) all state variables?
  - What if only a subset of state variables can be measured in practice?
- **Problem**: How to identify minimum set of sensors whose measurements can allow us to determine all state variables
  - What is the impact of noise and measurement uncertainties on determining the minimum number of sensors?

(This problem is still not solved*, though it may be possible to compute a lower bound for the number of system variables)

- Y-Y. Liu, J-J. Slotine, A-L. Barabasi, "Observability of Complex Systems," Proc. of the National Academy of Sciences of the USA, Feb 12, 2013.

Challenges on Implementing Controllability

- A system is called **controllable** if it can be driven from any initial state to any desired final state in finite time using a suitable choice of input
  - This is like capturing an ability to guide a system's behavior towards a desired state via proper manipulation of input variable*
- **Problem 1**: How to identify the minimum number of driver nodes to achieve controllability
  - How to characterize and predict driver node
- **Problem 2**: How to avoid having perfectly (or nearly-perfectly) attackable systems
  - How to distinguish a compromised system from a healthy system

- Y-Y. Liu, J-J. Slotine, A-L. Barabasi, "Controllability of Complex Systems," Nature, vol. 473, 12 May 2011.

An Example for Identifying Critical Nodes and Controllable Input Signals

Determining Risk, Resilience, and Control Effectiveness of Cyber Assets

- Determine individual risk, resilience, and control effectiveness of cyber assets within a node using various techniques, including a Bayesian network:

  P(A) , P(B): probability that node receives various threats.

  P(C) , P(D): probability that node has vulnerabilities that can be exploited by threats.

  P(E): probability that node receives aggregated threat.

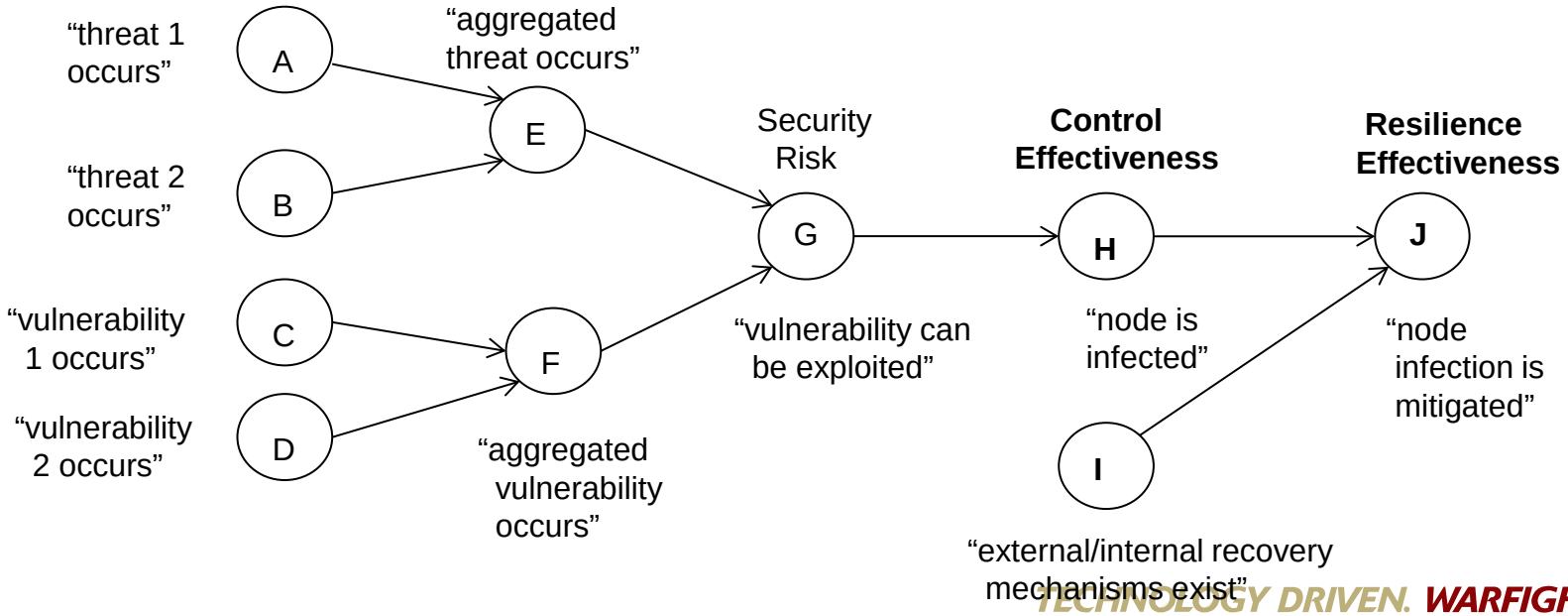
  P(F): probability that node has aggregated vulnerabilities that can be exploited by threats.

  P(G): probability that vulnerability can be exploited at node.

  P(H): probability that node is infected despite the presence of control mechanisms.

  P(I): probability that node has proper internal/external recovery mechanisms for mitigating node's infection.

  P(J): probability that node infection is mitigated.



Identifying Critical Nodes based on Network Connectivity and Attributes

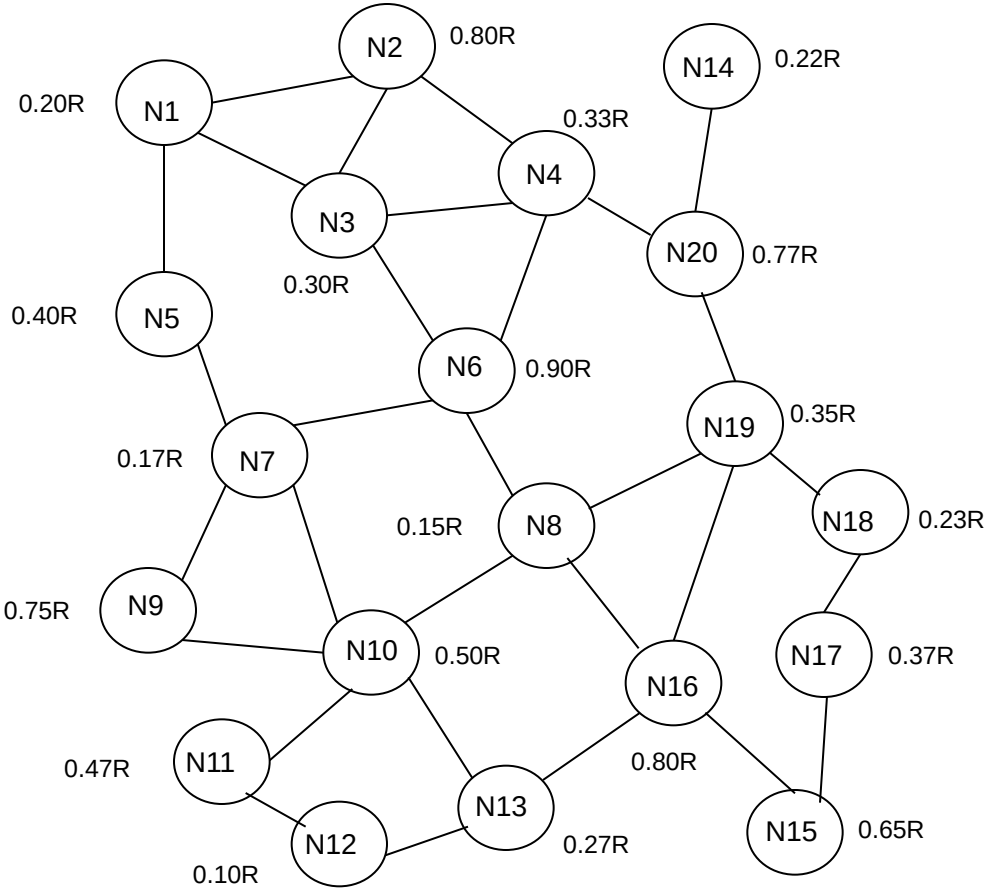
- Enable network connectivity to be considered along with node attributes (e.g., resilience, control, influence) in identifying and classifying critical nodes
- We develop **Hierarchically well-Separated Tree with Attributes (HSTA),** α-HSTA
  - obtained through Hierarchically well-Separated Tree (HST) to make it depend on not only the hops but also the attributes of nodes

– HST is usually used for resource matching and management

- **Construct** a Hierarchically Well-Separated Tree (HST) for a network of nodes
  - α-HST: a weighted tree
    - The edge weights from the root to leaf decrease by a factor of α
    - All root-to-leaf paths have the same hop distance
    - The weights from each node to its children are the same
  - For construction of α-HST, centralized (top-down approach) or distributed (bottom-up approach) algorithm is used
  - **2-HST** is considered often, where α = 2

Resiliency Values of Network Nodes and computing/constructing 2-HSTA

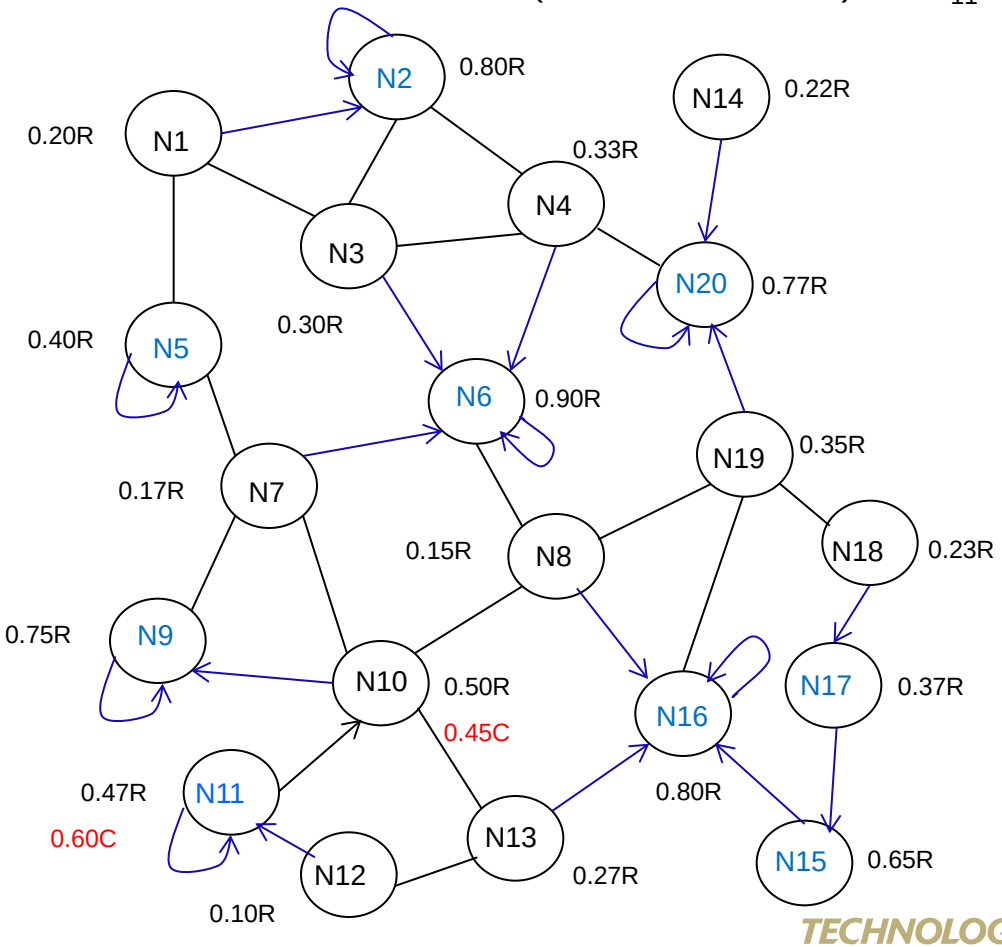
- Given (i) thresholds $T_r = 0.05$, $T_c = 0.10$ and $T_i = 0.08$, (ii) attribute values range from 0.1 to 1, where 1 is highest desirable attribute value, (iii) primary attribute values (i.e., resilience values) with subscript *R* are shown in graph
- All the nodes of this network are considered to be the leaves level (or level 1)



Flood 1-hop, and nominate level 1 ancestors in 2-HSTA

Flood each node 1-hop to determine the ancestors of all the leaves nodes

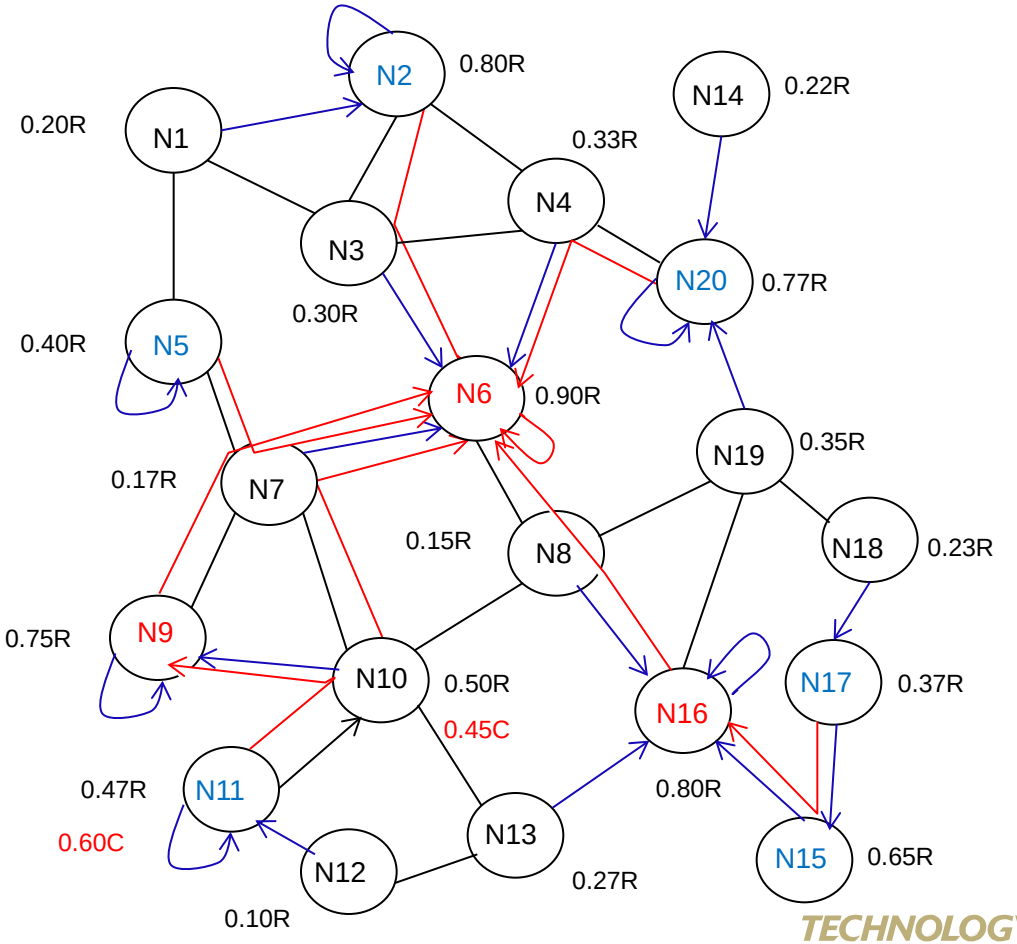
- compare resilience values, and choose highest one (shown with arrows in blue) if the difference of their resilience values is greater than $T_r = 0.05$; otherwise, consider their control values
  - For instance, note the difference between resilience values of N_{10} is N_{11} is less than 0.05
  - Compare their control attribute values (i.e., 0.60 and 0.45), so N_{11} does not nominate N_{10}



Nominated nodes at level 1 are:
N2, N5, N6, N9, N11, N15, N16, N17, N20

Flood 2-hops, and nominate level 2 ancestors in 2-HSTA

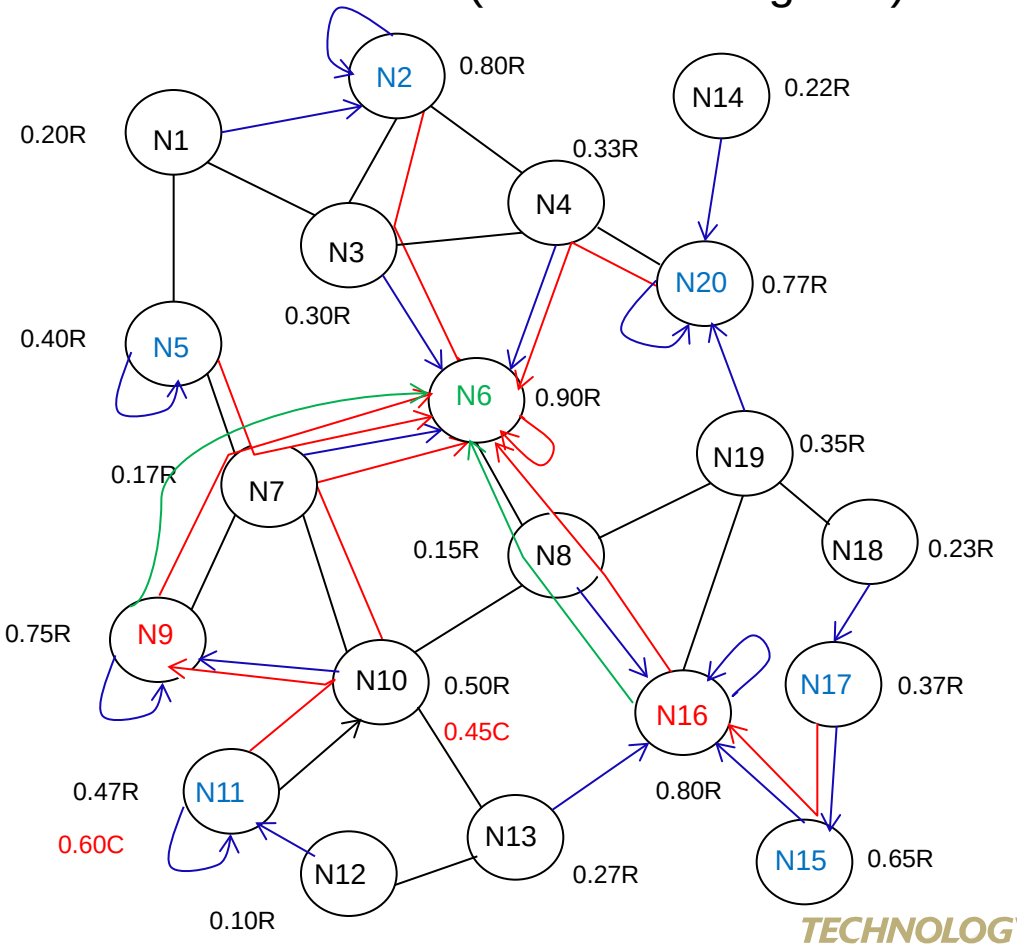
- For each node:
  - flood 2-hops to determine potential ancestors
  - compare resiliency values, and choose the highest resilience value
  - nominate level 2 ancestors (nodes with labels in red)



Nominated nodes at level 2 are: N6, N9, N16

Flood 4-hops, and nominate level 3 ancestors in 2-HSTA

- For each node:
  - flood 4-hop to determine potential ancestors
  - compare resilience values, and choose the highest resilience value
  - nominate level 3 ancestors (node label in green)



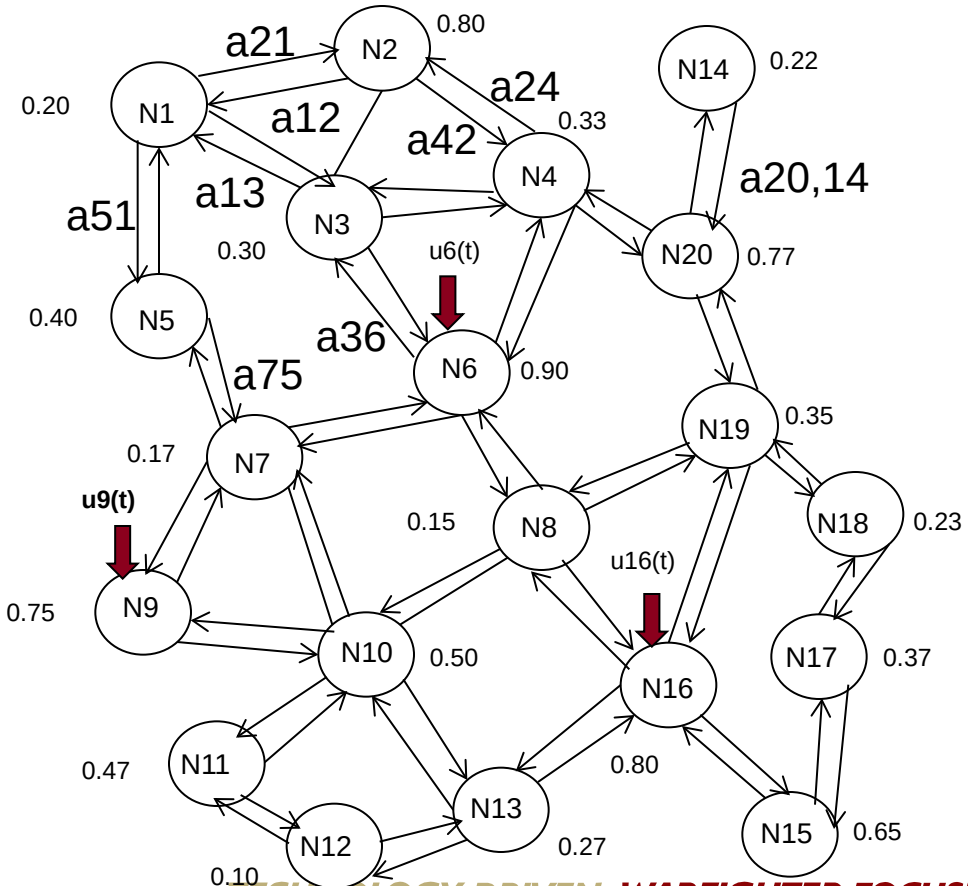
Nominated nodes at level 3 are: N6

Network Controllability Support by Resilience Critical Nodes

- Let the critical nodes of level 2 have external inputs controlled by an outside controller: N_6, N_9, N_{16} (called "driver nodes" for network controllability)
  - So, the external inputs $u_6(t)$, $u_9(t)$, and $u_{16}(t)$ are non-zero, and all the other external inputs of nodes are zero. This implies b_6, b_9, and b_{16} are non-zero.

- Compute the weights of resiliency dependencies or influences a_{ij} and a_{ji} between neighboring nodes i and j, for all nodes,

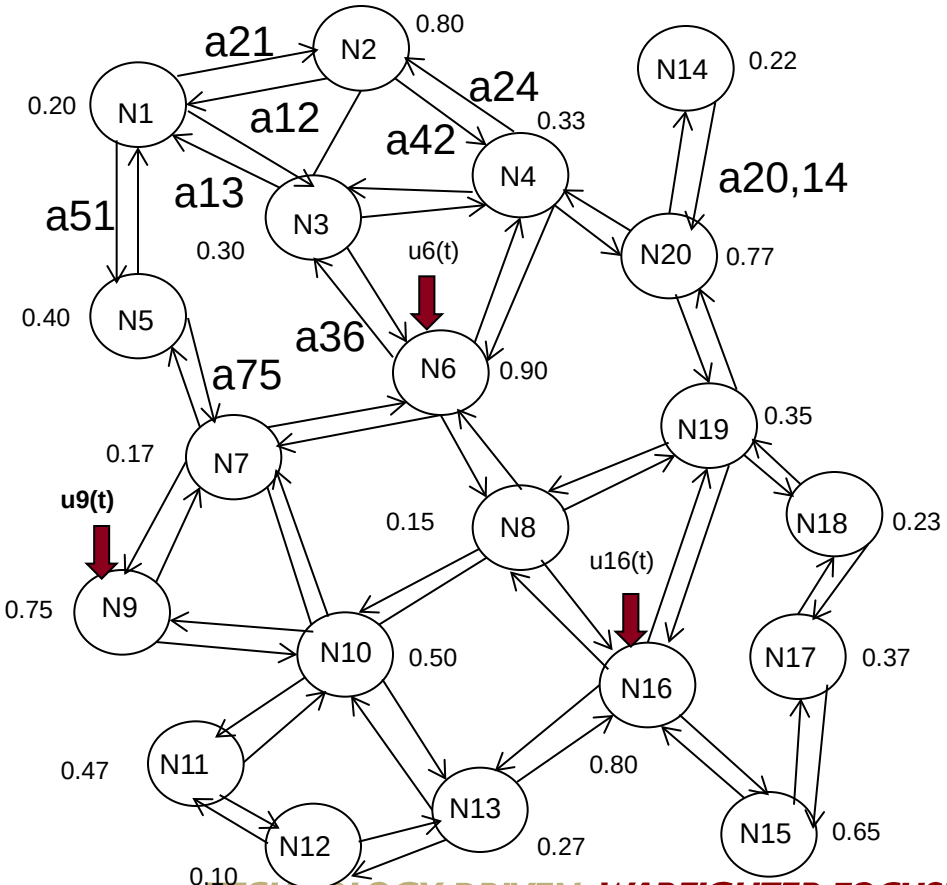
  where a_{ij} is the weight associated with the directed edge from j to i in the graph
- The same type of weights could be computed for other types of influences, namely, control, security, and vulnerability



Network Controllability Support by Resilience Critical Nodes (cont'd)

- Consider a network comprising N nodes or assets, where **each node i is associated with a status vector $x_i(t)$** that describes the physical properties of the node at time *t*

- Define a directed graph G with N vertices such that a directed edge from vertex i to vertex j indicates that the status of node j directly depends on the concurrent status of node i
  - an edge from a vertex back to itself indicates that the status change of the vertex depends on its current status
- **The status trend or update of a node** depends on the current status of itself, neighbors, and local input



$$A = \begin{bmatrix} a_{11} & \dots & a_{1,20} \\ \vdots & \vdots & \vdots \\ a_{20,1} & \dots & a_{20,20} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ b_6 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & b_9 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & b_{16} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

The N x NM controllability matrix:

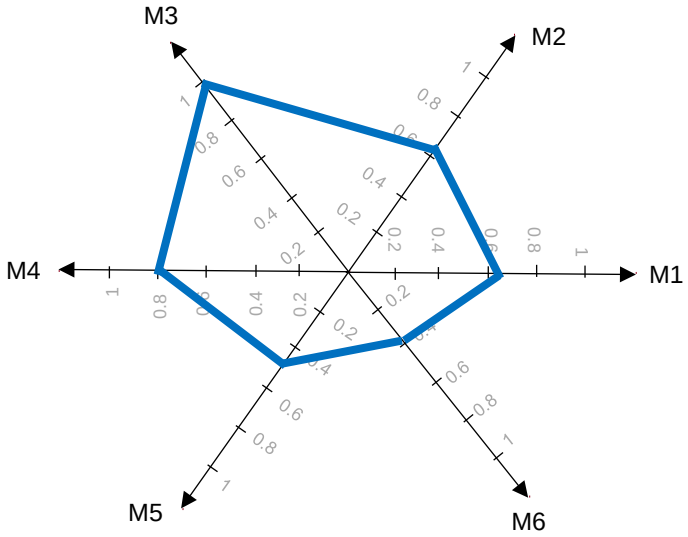
$C = (B, AB, A^2B, \dots, A^{N-1}B)$

If rank(C) = N, system is controllable

$$B^T = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & b_6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & b_9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & b_{16} & 0 & 0 & 0 \end{bmatrix}^T$$

Criticality Surface Polygon for Aggregating Metrics

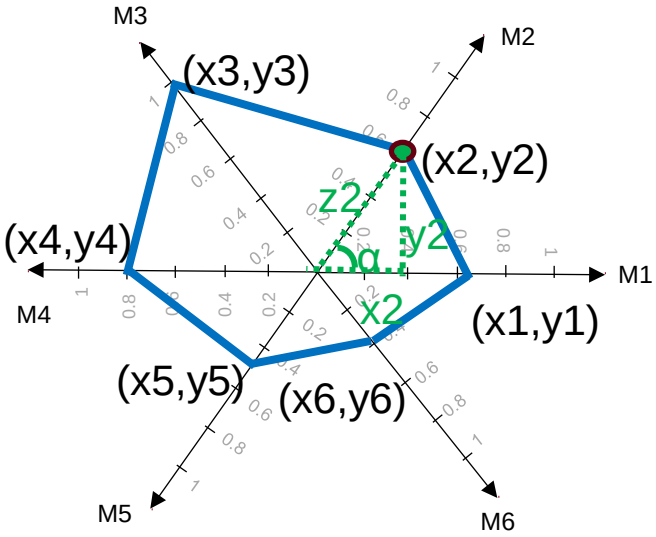
- Equiangular polygon
  - Consider metrics, Mi, i > 1
  - As an example, let i=6
    - M1: risk
    - M2: resilience
    - M3: control
    - M4: influence
    - M5: recovery
    - M6: robustness
  - Angle: 360/6 = 60 degree
  - Each metric
    - initially, has its own unit and range
    - then, is normalized between 0 and 1
- The (2-dimensional) area of polygon is defined as being the criticality surface of its metrics



Area Calculation of Criticality Surface Polygon

- Determine coordinates of equiangular polygon
- Consider a polygon with N-1 sides and N vertices (x_i,y_i), i=0 to N-1, such that the first vertex (x_0,y_0) and the last vertex (x_N,y_N) are the same
- Area of this polygon is given by

$$\text{Area} = \frac{1}{2}\sum_{i=0}^{N-1}(x_i y_{i+1} - x_{i+1} y_i)$$



$x2 = z2 \cdot \cos\alpha$

$y2 = z2 \cdot \sin\alpha$

Questions?