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CSYS 300 – COMPLEX SYSTEMS FUNDAMENTALS, METHODS & APPLICATIONS

Resilience Methods and Applications

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NNSA National Nuclear Security Administration

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Outline of Presentation

- Brief Biographical Note
- Where this Section Fits in the Structure of the Complex Systems Course
- Brief Survey of Methods and Application Areas
- The Infrastructure Resilience Analysis Method (IRAM)
- A Case Study
- Summary
- Question & Answer Session

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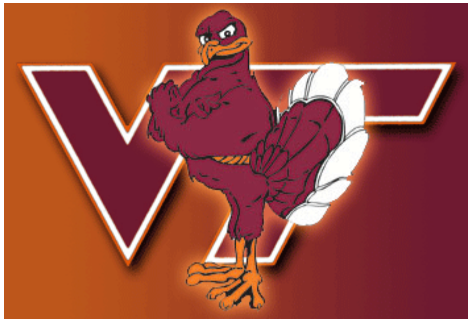
Resilience Methods and Applications



Brief Biographical Note on Eric Vugrin

- Education:
  - PhD in Mathematics from Virginia Tech
  - Concentration in optimal control, distributed parameter systems, numerical analysis

- SNL Work Experience
  - 2004-2008: total systems performance assessment for the Waste Isolation Pilot Plant (WIPP)
  - 2008-current: infrastructure modeling and analysis, including
    - Characterization of economic criticality of chemical manufacturing facilities
    - CANARY water event detection software
    - Infrastructure <u>resilience</u> characterization and optimization

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Structure of the Course

	Focus of this session
▪ Fundamentals of Complex Systems	☐
▪ Methods	
▪ Modeling Techniques	☐
▪ Approaches to Examining Complex Systems	☑
▪ Applications	
▪ Examples of the use of complex systems fundamentals to solve problems	☐
▪ Learning how to use complex systems **analysis** tools	☑

*Note: These approaches represent a simplified set of complex systems concepts chosen for the CSYS500 systems lectures. Please see the initial two lectures for additional detail and expanded references.

Evolution of Security Philosophies

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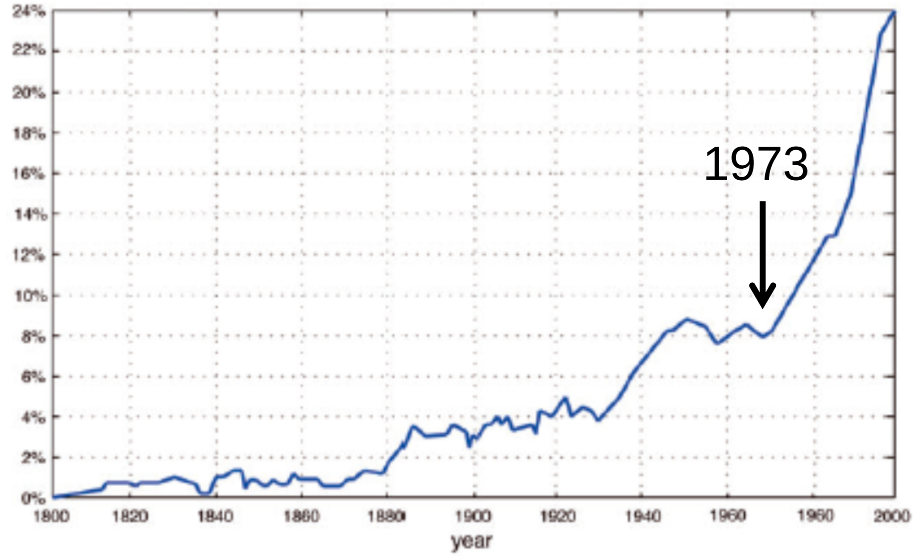
Physical Protection → **Risk Analysis** → **Resilience**

"Protection in isolation is a brittle strategy"
-Homeland Security Advisory Council (2006)

“Resilience is not a new idea.”

-Tom Corbet (2008)

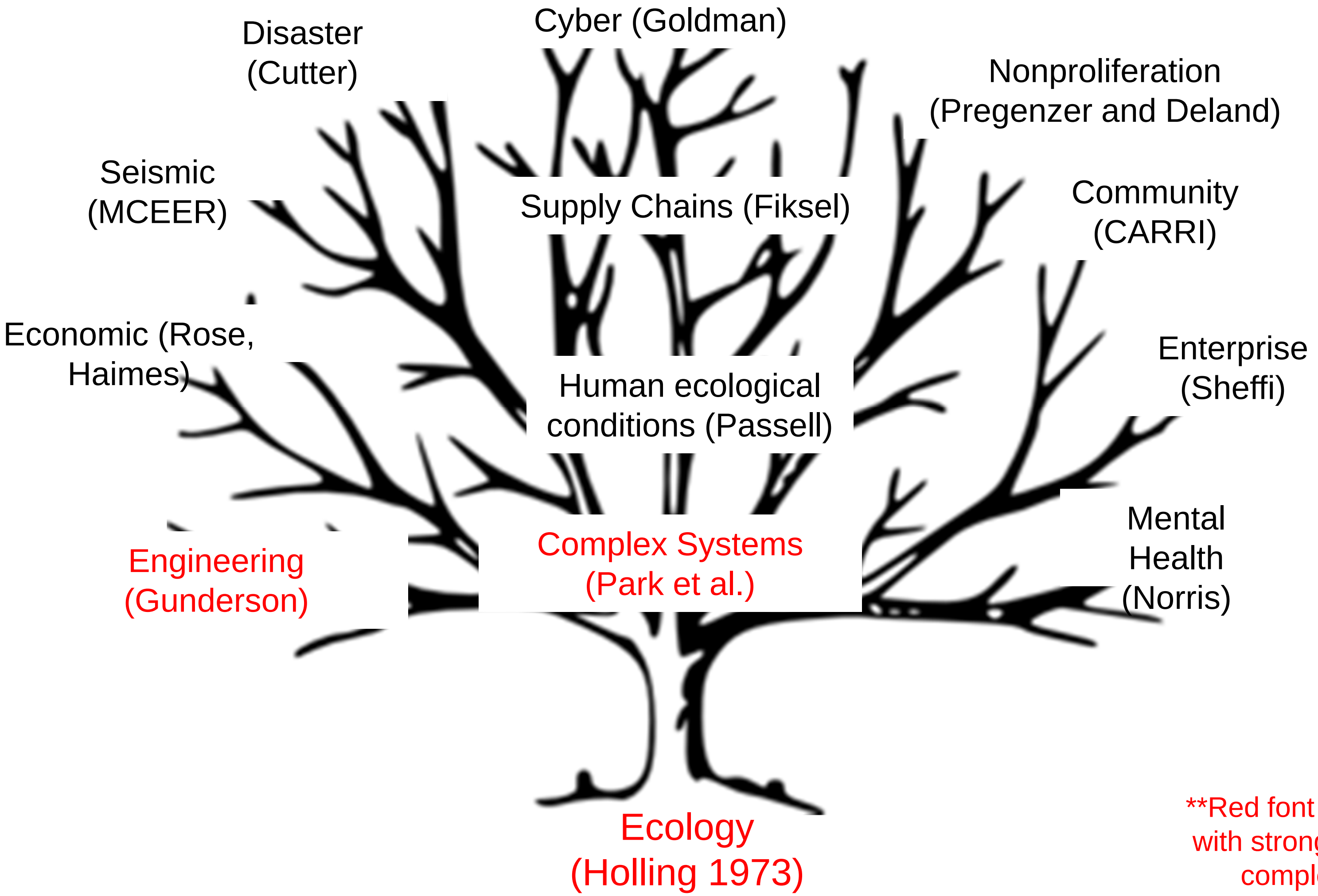
Frequency of “resilience” in print*



*Source: Park et al. 2013

- 1903: resilience defined in thermodynamic context
- 1973: C.S. Holling introduces resilience in an ecological context as complex systems property
  - Measures resilience by the magnitude of the disturbance that can be absorbed before the system redefines its structure

Domains of Study



**Red font indicates areas with strong connection to complex systems

Definitions: many options, no consensus

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- Dozens of definitions exist
- Common concepts included in definitions include
  - Withstand changes from external force
  - Absorb impact
  - Adaptation
  - Rate of recovery
- Literature highlights two major definition types
  - Ecological resilience: measured by magnitude of disturbance required to move system to new "stability domain"
  - Engineering resilience: ability to return to a steady state following a disturbance

"The term 'resilience' means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents."

-Resilience definition from PPD-21

Analysis Methods: 2 Major Categories

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Attribute-Focused

- Central question: "What makes the system resilient?"
- Analyzes system attributes to ID strengths/weaknesses
- Qualitative or semi-quantitative
- Pros
  - Limited data requirements
  - Direct link to attribute focused definitions
- Limitations
  - Inherent subjectivity makes cross-system comparison difficult and questioned

Performance-Focused

- Central question: "How resilient is the system?"
- Analyzes system outputs via quantitative metrics
- Pros
  - Less subjective/more objective
  - Metrics make cross-system comparison easier
- Limitations
  - Does not explain "Why?"
  - Interpretation of unitless quantities
  - Can be model-specific
  - Less direct connection to definitions

Infrastructure Resilience Analysis Methodology (IRAM)

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- IRAM is a "hybrid" methodology focusing on both performance-metrics and attribute analysis
- IRAM consists of 4 primary components
  - Definition: measurement focus sets up metrics
  - Metrics: include both performance and resources
  - Attribute analysis: explains quantitative results and IDs improvement options
  - Process: formalizes application of the IRAM
- Though initially developed for infrastructure systems, the IRAM is generally applicable to complex systems

Questions to Address

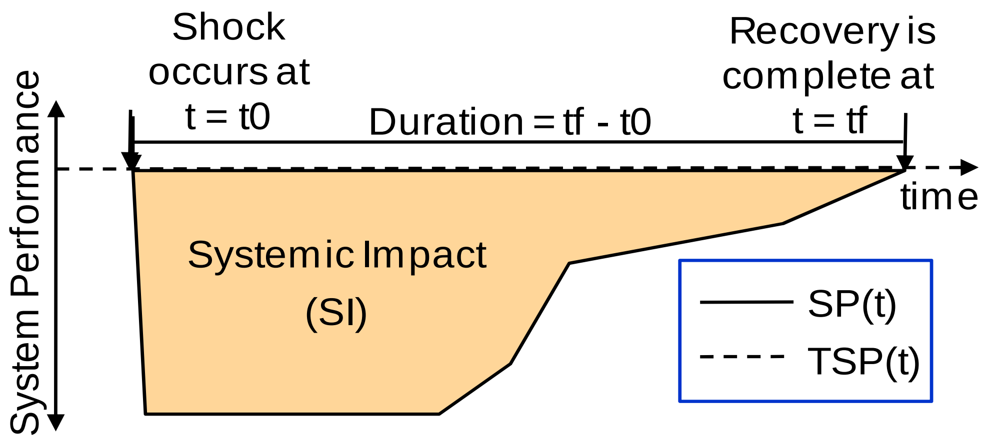
- How resilient is the current system?
- What are costs/impacts associated resilience and disruptions?
- What system features limit resilience and how can they be improved?
- Which recovery strategies enhance (optimize) the system resilience?
  - What are the resource requirements and costs associated with those strategies?
- In an uncertain environment, how can one effectively (optimally) invest in resilience?

Definition: Key Points

> *"Given the occurrence of a particular, disruptive event (or set of events), the resilience of a system to that event (or events) is the ability to reduce efficiently both the magnitude and duration of the deviation from targeted system performance levels."*
>
> *-Vugrin et al., 2010*

- Context matters
  - Disturbance type
  - System structure
  - Resources
- Performance
  - Magnitude and duration
  - Target level
- Efficiency is "tip of the hat" to importance of resources

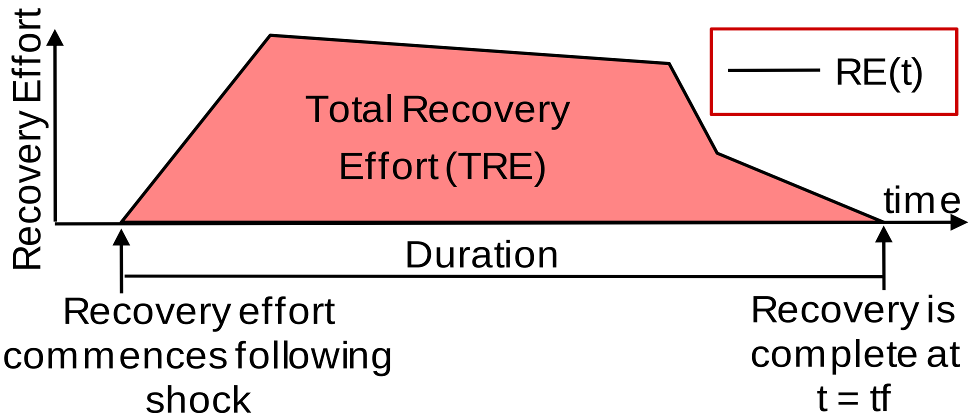
Metrics: Systemic Impact (SI)



$$SI = \int_{t0}^{tf} \left\{ \sum_{j} q_j(t) \left[TSP_j(t) - SP_j(t) \right] \right\} dt.$$

- Notes:
  - SI is cumulative impact on performance
  - TSP can vary over time
  - Allows multiple performance metrics
  - Similar formulations for discrete time

Metrics: Total Recovery Effort (TRE)



$$TRE = \int_{t0}^{tf} \left\{ \sum_k r_k(t) \left[RE_k(t) \right] \right\} dt$$

- Notes:
  - TRE represents cumulative resource expenditure
  - Allows multiple resource categories
  - Similar formulations for discrete time

Metrics: Two Indices

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$$RDR\left(d, RE, SP\left(t0\right)\right) = \frac{SI + \alpha \times TRE}{Norm}$$

As RDR increases, resilience decreases

$$Norm = \int_{t0}^{tf} \left\{ \sum_j q_j\left(t\right) \left|TSP_j\left(t\right)\right| \right\} dt$$

- RDR = "recovery dependent resilience" index
  - Measures cumulative "cost" of disruption
  - Explicitly depends upon recovery actions
- $Norm$ quantifies magnitude of system and allows comparison of different sized systems
- α = weighting factor between performance and resources
- Most useful for comparison

Metrics: Two Indices

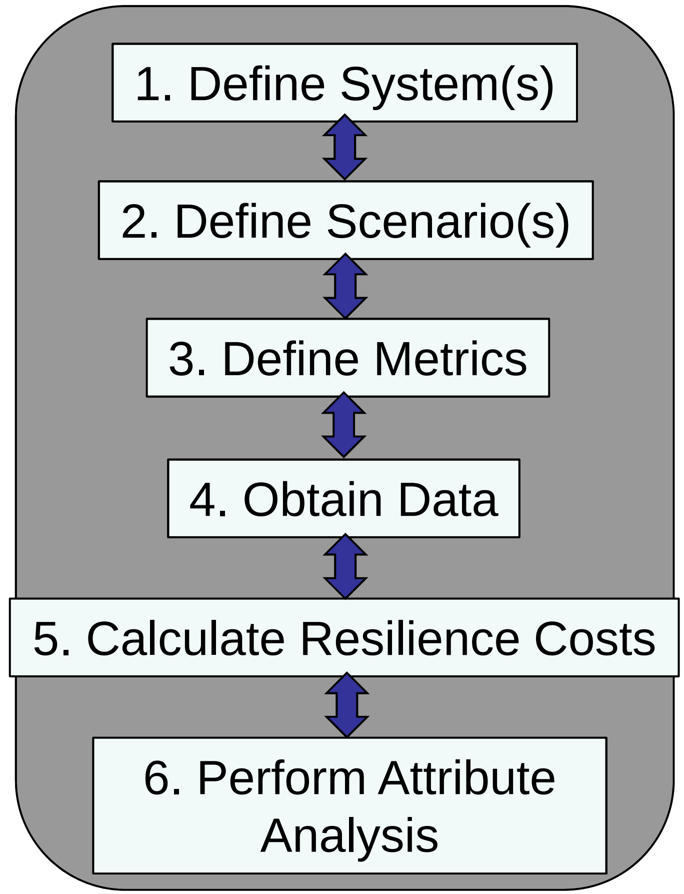
$$OR\left(d, SP\left(t0\right)\right) = \min_{RE} \frac{SI + \alpha \times TRE}{Norm}$$

- *OR* = "optimal resilience" index
  - Minimum cumulative "cost" across all feasible recovery options
- Likely requires model
- Optimal recovery option may not exist or be unique

Attribute Analysis: 3 Capacities

	Absorptive Capacity	Adaptive Capacity	Restorative Capacity
Directly Impacts	Systemic Impact	Primarily Systemic Impact, but also TRE	Total Recovery Effort
Distinguishing features	Automatic manifestation after disruption	Reorganization and change from standard operating procedures	System repair
Temporal Sequencing	First line of defense	Second line of defense	Final line of defense
Post-disruption event required	Automatic/little effort	Increased effort	Greatest effort
Duration of changes	Permanent	Temporary	Permanent
Resilience enhancement feature examples	Stored inventory; robustness; redundancy; segregation	Substitution; rerouting; conservation; reorganization; ingenuity	Advance warning and monitoring systems; pre-positioning; reciprocal aid agreements

Process

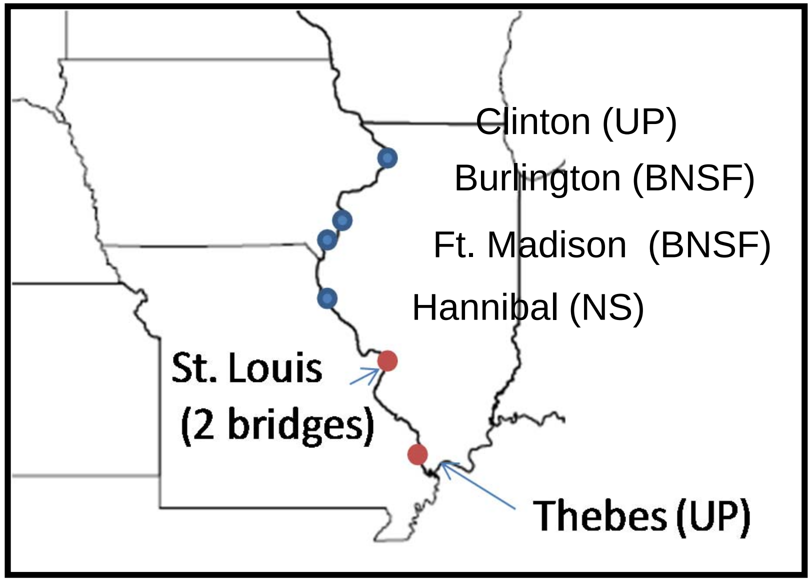

1. Define System(s)
2. Define Scenario(s)
3. Define Metrics
4. Obtain Data
5. Calculate Resilience Costs
6. Perform Attribute Analysis

Example Study: Rail Networks

- Fundamental question: what is the optimal recovery sequence that maximizes resilience of the rail carriers to a flooding event, given that
  - Recovery resources are limited;
  - Multiple recovery modes are available;
  - Multiple restoration sequences are available.
- Focus of study on measurement and optimization, so we will skip the attribute analysis

Steps 1 and 2: ID system and hazards

- System: US freight rail system
- Scenario:
  - 4 rail bridges on northern Mississippi out due to flooding
  - 3 bridges unaffected
  - East-West rail traffic significantly affected
  - Chicago is the largest east-west interchange point
  - Traffic between Chicago and Kansas City, Omaha and Denver expected to be disrupted



Steps 1 and 2: ID system and hazards

- Adaptation option (rerouting): delay times and increased distances increase operating expenses
- Recovery options: 3 modes to repair bridge
  - Normal mode is most cost effective repair mode
  - Emergency mode: most expensive but additional costs may be justified to avoid large system impacts
  - Staged mode: allows restoration of partial capacity
  - Assumption: 3 "resource units" may be spent at any given time

Mode	Duration	Cost	Capacity Restored	Resource Units
Normal	15 days	$5M	100%	1
Emergency	10 days	$10M	100%	2
Staged	9 days	$3M	50%	1

Step 3: ID Metrics

- System performance (SP)= daily revenue from carload movement Iowa, Illinois, Nebraska, Kansas and Missouri
  - TSP = “nominal” daily revenue from carload movement
  - SI = lost revenue from carloads not moved
- TRE: cost of rerouting plus recovery activities
  - Additional operating cost from increased time
  - Additional operating cost from increased distance
  - Bridge repair costs

Step 3: ID Metrics

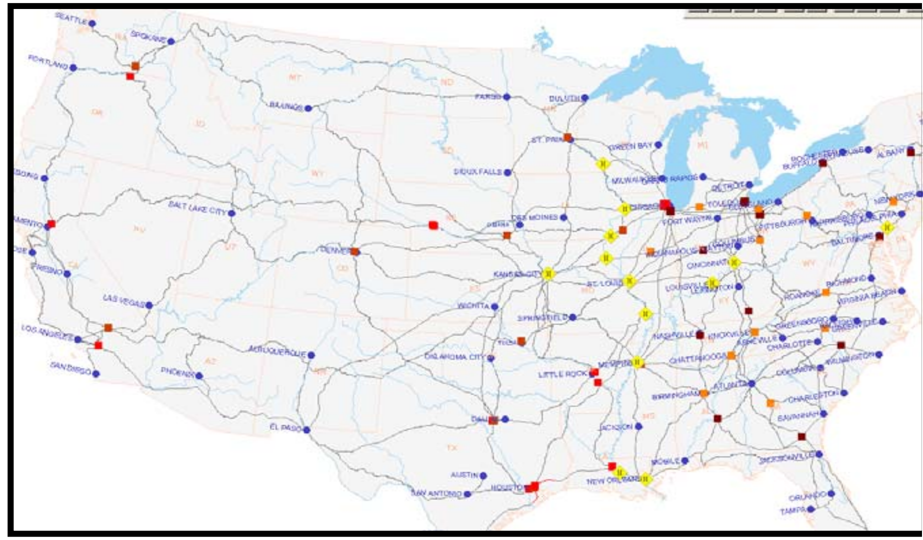
Category	Variable	Cost
Additional car-miles	ACM	$1.50/car-mile
Additional Transit Time	ATT	$38/car-day
Carloads not moved	CNM	$1770/load
Bridge Repairs	BR	TBD

$$SI = \sum_t \left[1770\, CNM(t) \right]$$

$$TRE = \sum_t \left[1.5\, ACM(t) + \frac{38}{24} ATT(t) \right] + BR$$

Step 4: Obtain Data (Simulation Tool)

- Basis for model: Rail Network Analysis System (R-NAS)
  - Static, nonlinear optimization model developed by NISAC for consequence analysis
  - R-NAS solves for network flows under the assumption that car-miles are minimized
  - Distances and congestion “delay functions” determine travel times and distances

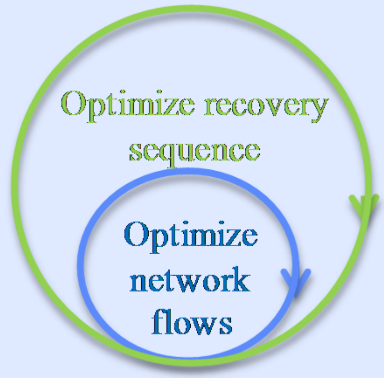


R-NAS Simulation

- Model was adapted to add dynamics or recovery
  - Network flows change as repairs are completed
  - Costs to the rail carriers decrease as repairs completed
  - Systemic impact measured from initiation of disruption to return to baseline conditions

Step 4: Obtain Data (Optimization Model)

- Optimization resembles Multimodal Resource Constrained Project Planning (MRCPP) problem
- Bilevel optimization problem
  - Outer loop: optimize recovery sequence that minimizes resilience costs w/ resource constraints
  - Inner loop: optimize flows for specified network state



Bilevel programming model

- Simulated annealing (SA) algorithm (Boctor 1996) solves outer loop problem and searches space of feasible recovery sequences
  - For a given recovery sequence, R-NAS solves inner loop optimization and reports resilience costs
  - SA algorithm analyzes R-NAS output and identifies “optimal” recovery sequence
  - Algorithm modifications developed to enhance computational efficiency

Step 4: Obtain Data (Results: 4 bridges out)

Commodity Group	Additional Car-Miles	% Change	Additional Car-Hours	% Change	Not Moved
Coal	169929	2.9	294479	97.2	58
Grain	-26182	-2	6892	3.2	700
Chemicals	28220	1.6	14234	3.3	819
Intermodal	213801	15.4	31928	48	1146
Motor Veh	45550	3.2	61109	87.1	355
Other	88613	1.6	15616	1	2539
Total	519931	3	424258	15.9	5617

- Daily lost revenue (CNM) = $9.9 M/day
  - # of cars moved decreases by > 1/3
- Daily ACM= $830k
- Daily ATT= $700k
  - Average additional car-hours increase: 16%
  - Nearly double for coal and motor vehicles

Step 5: Calculate Resilience Costs

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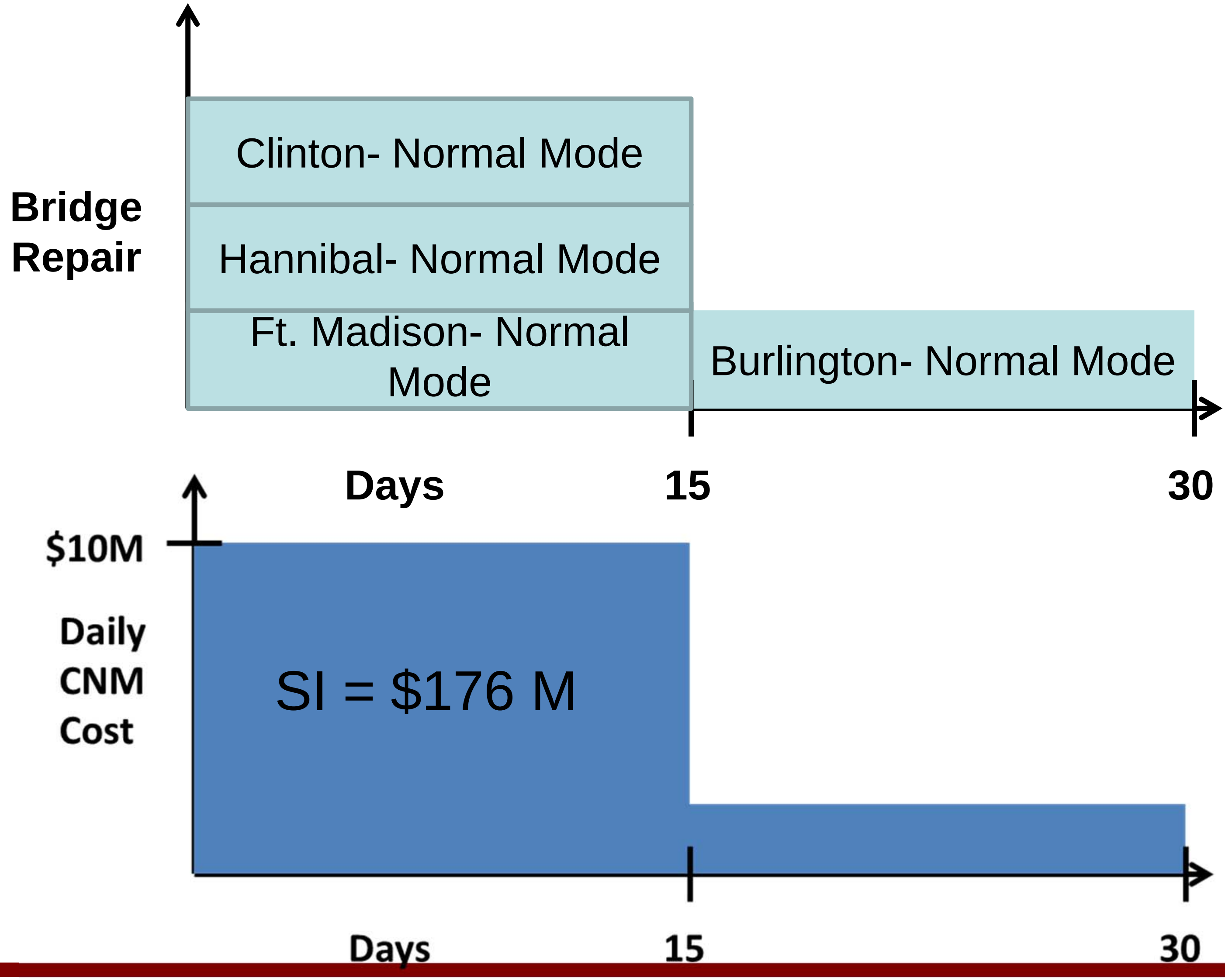
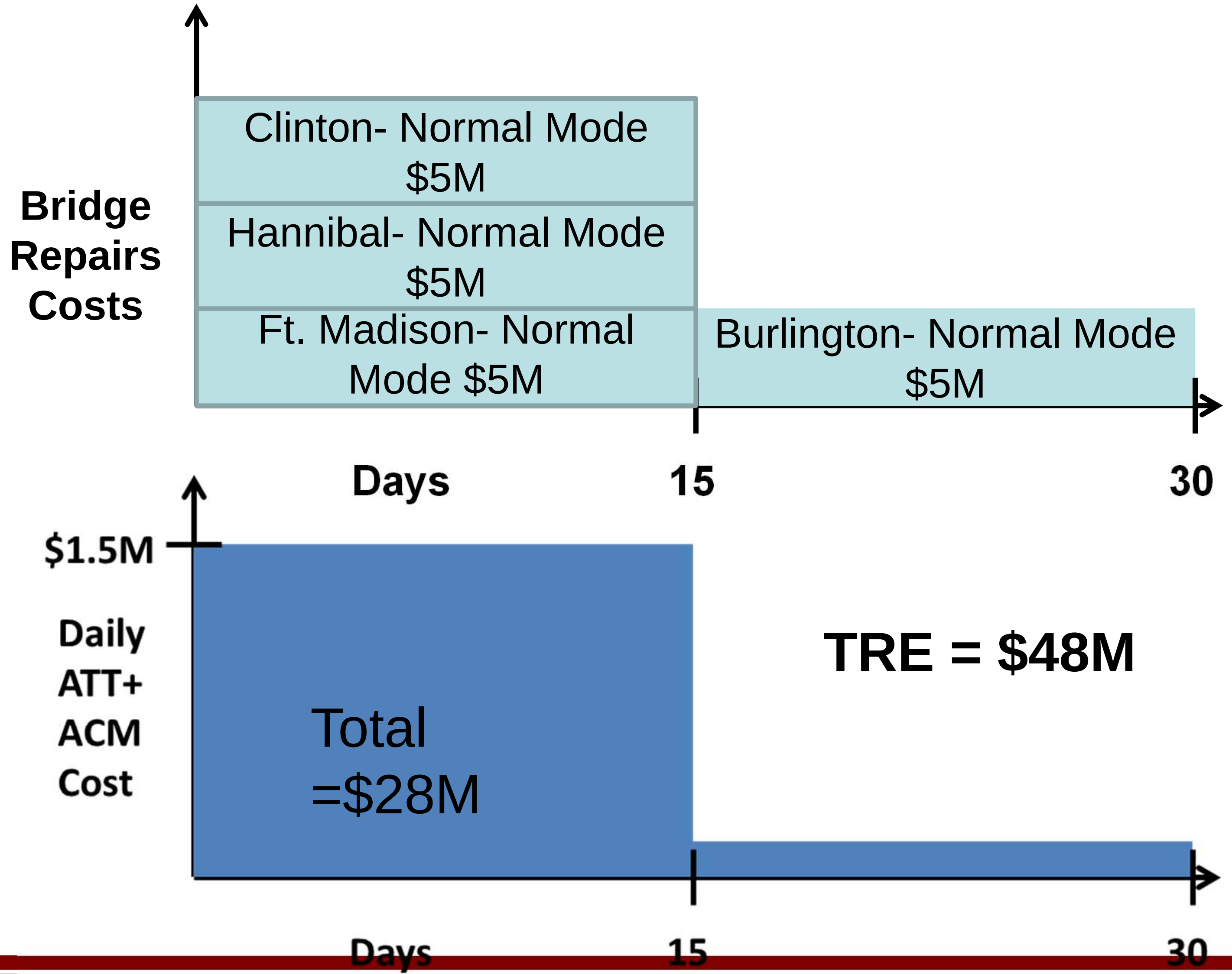
Recovery sequence for nominal case, no cooperation



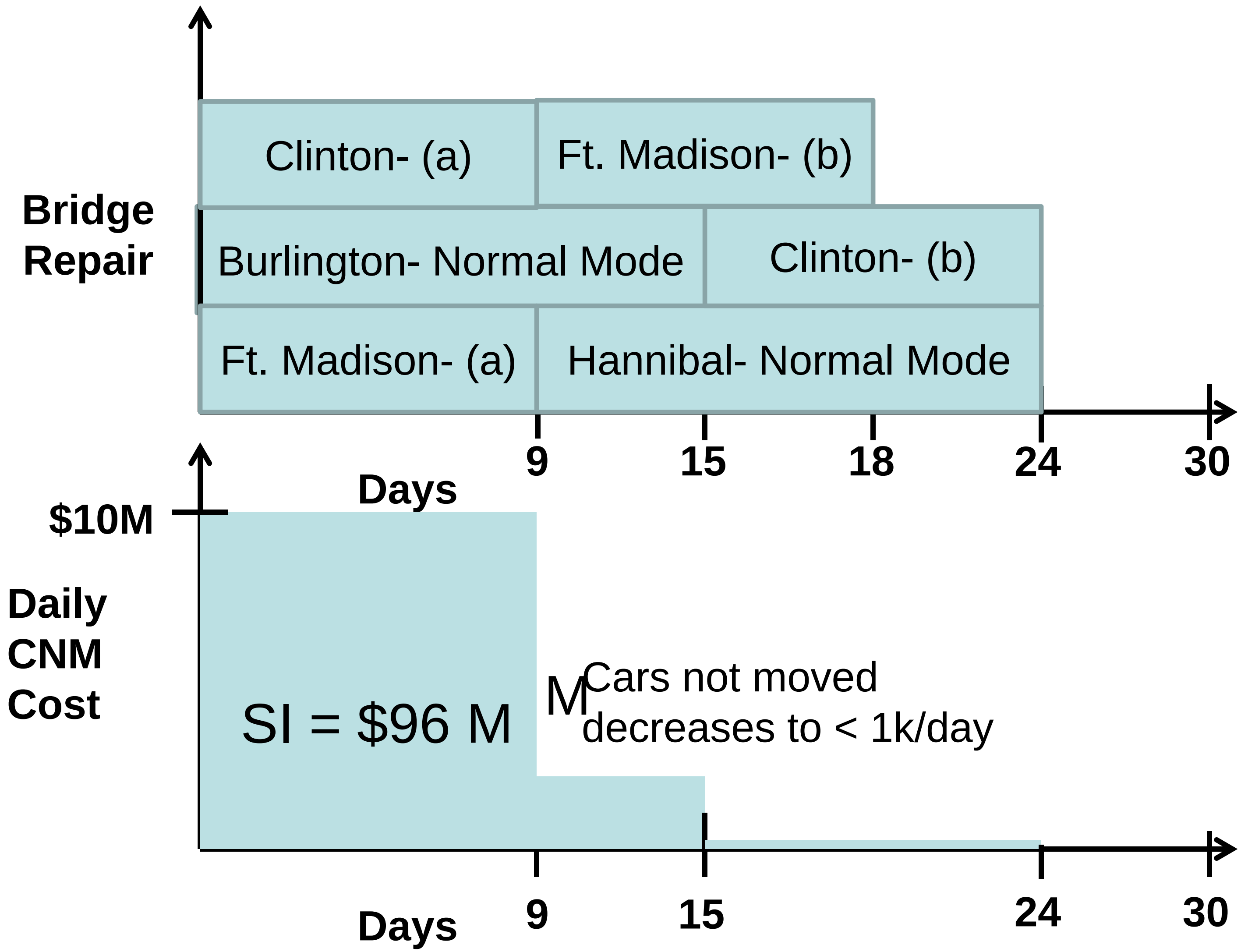
Step 5: Calculate Resilience Costs

Recovery sequence for nominal case, no cooperation



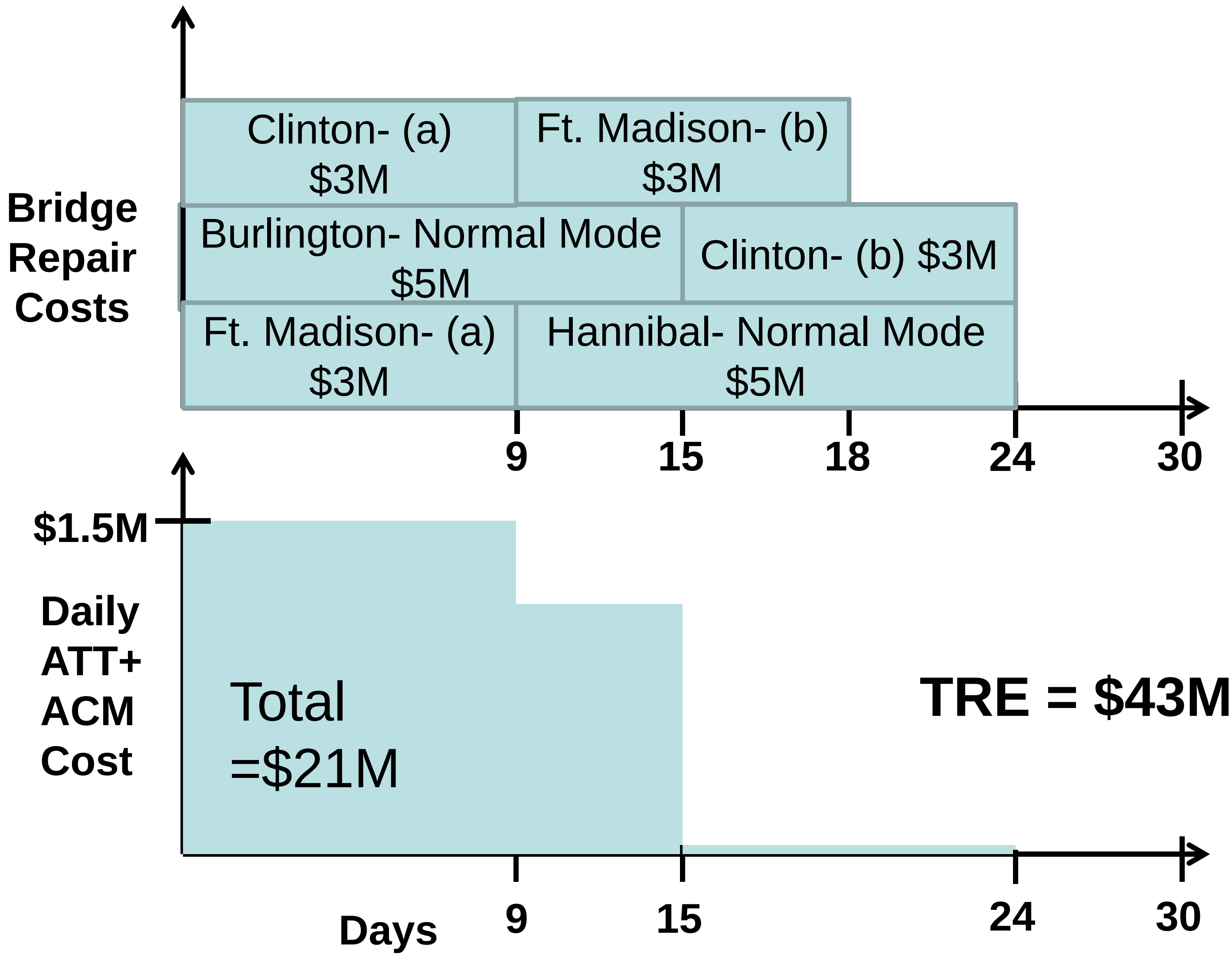
Step 5: Calculate Resilience Costs

Optimal recovery sequence, i.e., pool resources



Step 5: Calculate Resilience Costs

Recovery sequence for nominal case, no cooperation



Comparing Two Strategies

	Days To Complete Recovery	Systemic Impact	Total Recovery Effort
Cooperative Approach	24	$96M	$43m
Non-cooperative Approach	30	$176M	$48M

- **Cooperative approach**
  - Decreases time to recovery by 6 days
  - Decreases SI by $80M (45%)
  - Decreases TRE by $5M (10%)
  - Decreases total resilience costs by $85M (38%)

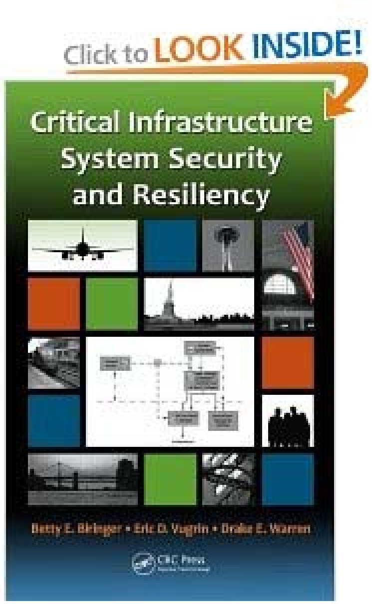
Summary

- Resilience is not a new concept
  - Lots of work, but little consensus
- Resilience has recently emerged as a key national and homeland security priority
  - It doesn't seem to be going anywhere, yet
- For these two reasons, Sandia ought to be involved in the "formalization" of resilience analysis
  - Science, tools, policy, etc.
- The IRAM represents an attempt to do so for infrastructures

Future Opportunities

- Span the “bang”
  - Resilience is about more than response
  - Investment and design decisions matter
- Get uncertain
  - Initial research performed into hazard/scenario uncertainty
  - Other sources of uncertainty matter and need to be considered
- Deal with the “human in the loop”
  - Need better tools/methods to understand resilience of integrated engineered and human systems

IRAM Resources



Critical Infrastructure Security and Resilience
Biringer, Vugrin, and Warren (2013)

CASOS Website:
http://www.sandia.gov/CasosEngineering/resilience.html

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QUESTIONS & ANSWERS

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