A Taxonomy of Perturbations: Determining the Ways That Systems Lose Value

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Value Robustness of Systems

- Engineered systems are designed to deliver value for stakeholders.
  - Value being some utility or benefit to the stakeholders, at some cost
- Systems *fail* when they no longer produce an acceptable value to stakeholders, during some specified period.
  - Failures of large, complex systems have been prominent in recent news:
    - Japanese nuclear power plants
    - Sony PlayStation Network (PSN)
    - Amazon's Elastic Compute Cloud

http://kbmt.images.worldnow.com

http://newsforblogging.blogspot.com

System architects want design principles that will make their systems value robust, i.e. perform effectively *no matter what*

Thus, system architects need to understand ***what*** causes systems to fail

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Perturbations, Disruptions and Disturbances

http://http://www.stabroeknews.com/images/2009/07/

Example scenario: Fire caused by lightning

- Suppose a structure is struck by lightning, ignites, and burns down

- **Perturbation**: Unintended state change of a system's form, operations or context, which could jeopardize value delivery
  - **Disruption:** Instantaneous, discontinuous perturbation (e.g. lightning)
  - **Disturbance:** Finite duration, continuous perturbation (e.g. fire)
- **Threat**: An external set of conditions that exist which may cause a perturbation, but hasn't impacted value delivery, yet. (e.g. thunderstorm)
- **Hazard:** An internal set of conditions inside a system that can cause a perturbation (e.g. flammable building materials).

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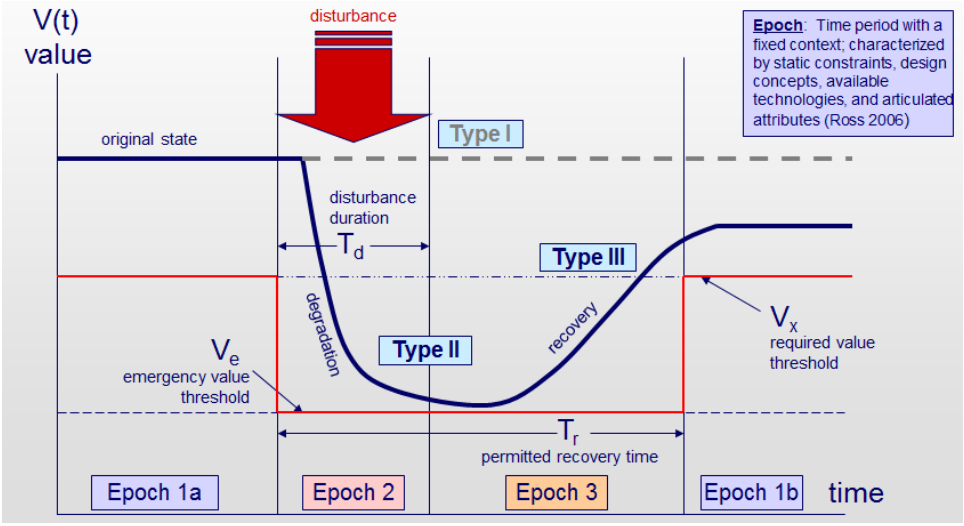
Survivability and Value Robustness

Survivability: The ability of systems to prevent, mitigate and recover from value delivery reduction as a result of some perturbations

Three Types of Survivability:

I. Prevention
II. Mitigation
III. Recovery



(Richards, 2009)

http://www.car-addicts.com/special-report/compensation-for-car-accident-injuries

Example Scenario: Automobile accident

Suppose an automobile manufacture wants to make its car "survivable" in the event of a collision.

- Active Type II survivability design principles are not applicable
  - No time to react
- Death or injury may be unrecoverable

Need to understand the nature of the perturbation to be survivable against them

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Making Systems Survivable

http://ruthiedean.com/2011/09/08/ruthie-vs-airplane-on-overcoming-fear/

Example scenario:

- Exhausted pilot flies through thunderstorm
  - Rain reduces visibility
  - Too tired to notice low altitude
- A wing gets damaged by clipping tower
- Plane spirals out of control, crashes, explodes

How can system architects make a plane survivable in such a scenario?

- Wing clip
  - Land safely with a damaged wing
    - Does the concept of operations include the fact that the weather is bad and the pilot is tired?
    - Could have done more damage
- Low visibility
  - Include windshield wipers
    - Similar problem at nighttime
    - May not matter if the pilot is tired

http://en.wikipedia.org/wiki/File:Emley_Moor_Tower_by_night.jpg

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Characterizing Perturbations, Threats & Hazards

Nature

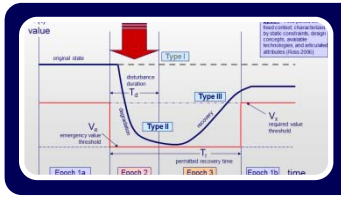
- How does the disturbance impact the system?

Origin

- Internal or external to the system
  - For many SoS, the lines are blurred.

Intent

- Is there an intent, by some entity, to cause this disturbance?



Length of Impact

- How long is the duration of the disturbance?
- Does the original context resume?

Effectiveness of a design principle will be strongly dependent on characteristics of the perturbations, threats & hazards

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Determining a Suitable Taxonomy

- Classifying perturbations by “type” is great if system architects want to focus on very specific perturbations and ignore others
  - E-commerce sites may want to focus on hacker attacks, while yogurt manufacturers may chose to ignore them
- However, dismissing entire classes of perturbations without analysis is risky
  - Assuming we know what to expect (“known unknowns”)
  - Some of the biggest system failures were the result of events that system architects never considered
    - 9/11 attacks
    - 2003 Northeast Blackout
- A solution to a particular problem, may be the solution to another problem as well
  - An authentication procedure can not only protect against hacker attacks, but also against unintentional actions by legitimate users.

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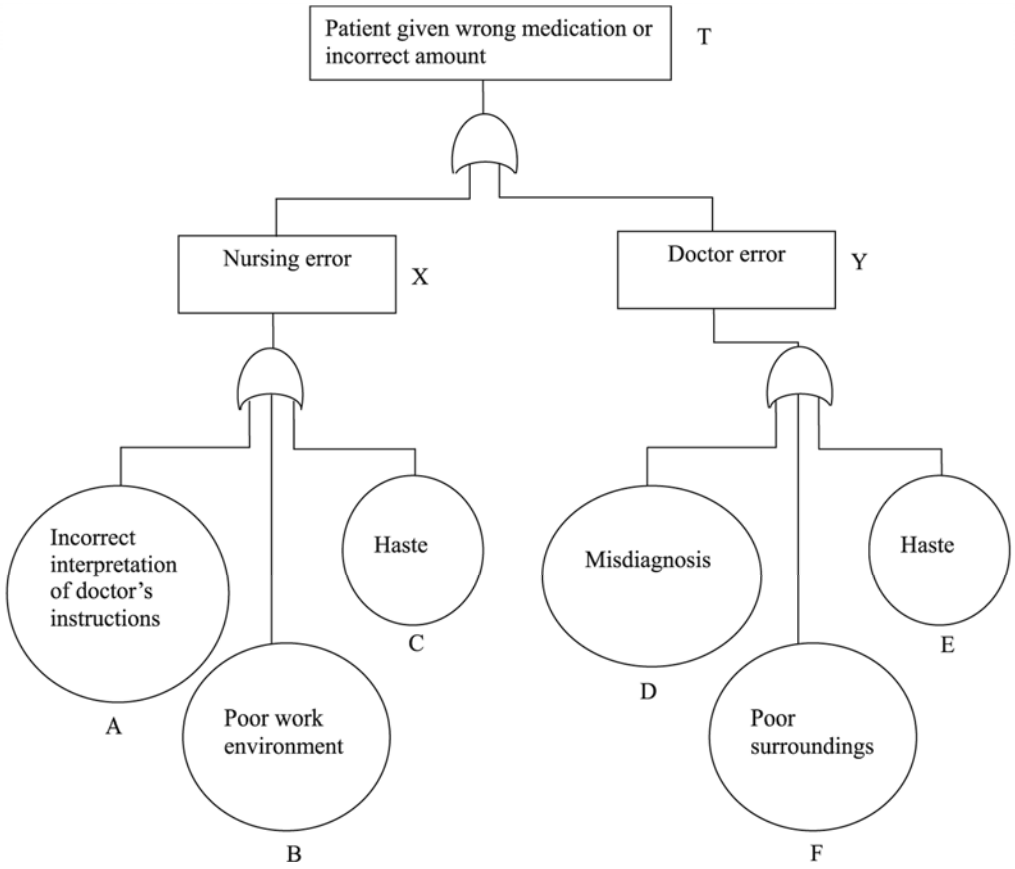
Analyzing Systems For Possible Perturbations

Fault Tree Analysis

- Top-down approach (Fenelon et al., 1994)
- Uses Boolean logic to determine cause of a *single* failure (effect)
- Deductive approach that often does not discover multiple effects of a single cause



http://www.emeraldinsight.com/journals.htm?articleid=841186andshow=html

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Analyzing Systems For Possible Perturbations

FMEA/FMECA

- Failure Mode Effects (and Criticality) Analysis
- Bottom-up approach
- Addresses "*loss of an intended function of a device*" i.e. component / capability failures, not operational / human failures (Langeford, 1995) (FAA, 2004)
- Very linear
  - Does not show multiple causes and effects or complex relationships well

Item Identification	Function	Failure Mode	Failure Cause	Failure Effect on		
				Component or Functional Assembly	Next Higher Assembly	System
Switch	Initiates Motor Power Function	Fails to Open	Release Spring Failure Contacts Fused	None	Maintains Energy to Circuit Relay	Maintains Energy to Pwr Circuit Through Relay
Battery #2 (Relay Circuit)	Provides Relay Voltage	Fails to Provide Adequate Power	Depleted Battery Plates Shorted	None Battery Gets Hot and Depletes	Fails to Operate Relay Circuit	Systems Fails to Operate
Relay Relay Coil	Closes Relay Contacts When Energized	Coil Fails to Produce EMF	Coil Shorted or Open	Does Not Close Relay Contacts	Does Not Energize Pwr Circuit	System Fails to Operate
Relay Contacts	Energizes and De-Energizes Pwr Circuit	Fails to Open	Contacts Fused	None	Maintains Energy to Motor	Overheated Pwr Circuit Wire if Motor is Shorted and Circuit Breaker Fails to Open
Motor	Provides Desired Mechanical Event	Fails to Operate	Motor Shorted	Motor Over-heats	High Current in Pwr Circuit	Overheated Pwr Circuit Wire if Circuit Breaker Fails to Open and Switch or Relay Fails
Circuit Breaker	Provides Pwr Circuit Fusing	Fails to Open	Contacts Fused Spring Failure	None	Maintains Pwr to Motor if Relay Contacts are Closed	Maintains Energy to Motor
Battery #1 (Pwr Circuit)	Provides Motor Voltage	Fails to Provide Adequate Power	Depleted Battery Plates Shorted	None Battery Gets Hot and Depletes	None	System Fails to Operate

http://www.fmeainfocentre.com/examples.htm

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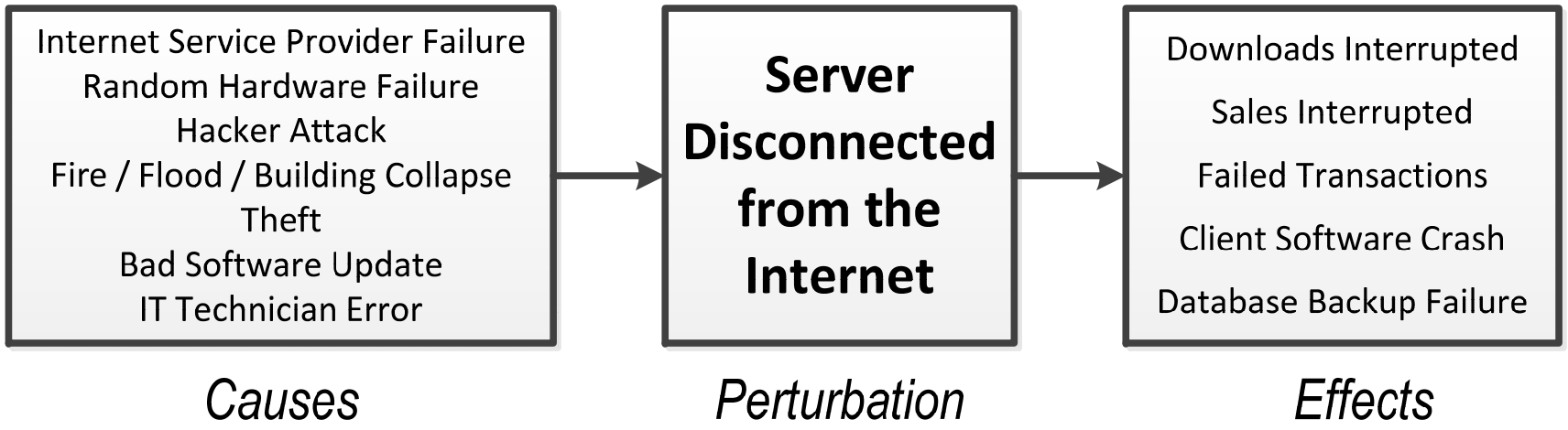
Cause and Effect

- Everything that causes a reduction in value delivery has at least one cause, and at least one effect.
- Each cause is a set of conditions that led to the perturbation.
- The effects are the change in context and/or system that are a direct result of the perturbation.



Exactly what caused a perturbation, may not be known, neither what effect(s) it has. These can be called *unknown unknowns*.

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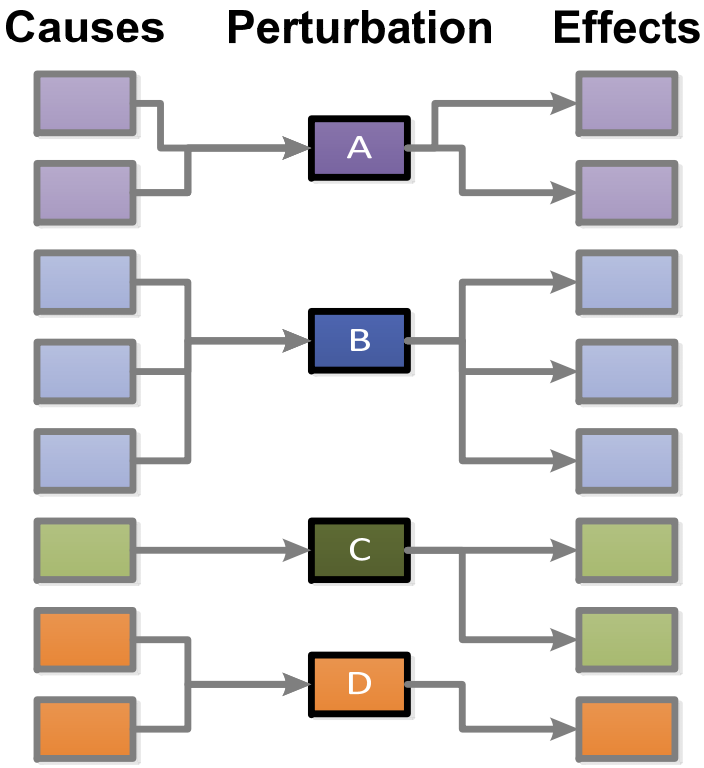
Multiple Causes, Multiple Effects

Many perturbations have multiple causes and/or multiple effects



- Not possible to make system survivable against all perturbations
- Constraints:
  - Budget
  - Time
  - Resources
- Qualitative characteristics of perturbations
  - Difficult to quantify
  - Difficult to model

Separating perturbations into cause and effect provides system architects with a qualitative way to prioritize causes / effects

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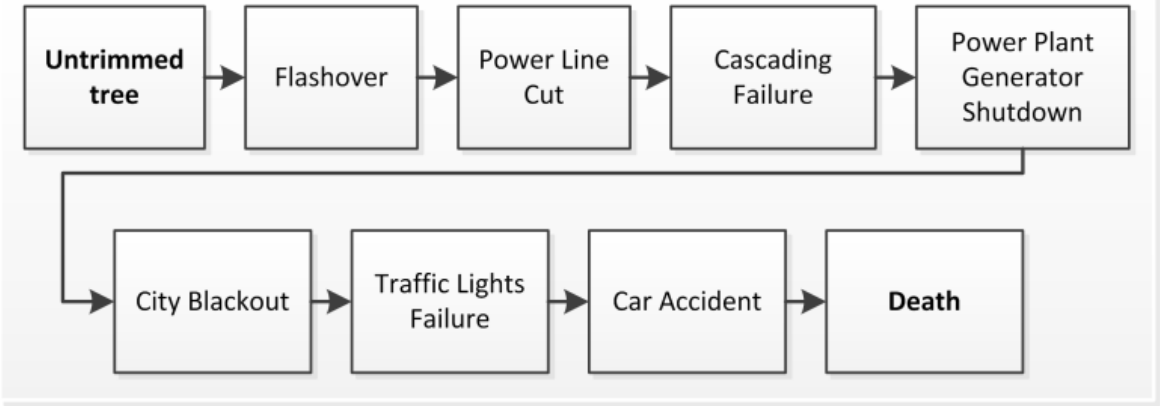
Cascading Failures

The effects of some perturbations, become the cause of others, in what's known as a *cascading failure*



http://en.wikipedia.org/wiki/File:Toronto_ON_2003_Blackout.jpg

Systemic Risk – The risk that a cascading failure will result from entities being too interconnected with each other

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Survivability and Intervention

http://www.impactlab.net/2008/04/14/laser-used-to-trigger-lightning-in-a-thunderstorm/

- Example: “Bad Weather”
  - How does one prevent “bad weather”
    - Bad weather is outside the system boundary
- System has a limited sphere of influence
  - Certain threats are outside the system boundary

An effect of “bad weather” is blurry images due to precipitation buildup on lenses.

- Cause – Precipitation on lenses
  - *Type I – Prevention by sheltering the lens*
- Effect – Blurry images
  - *Type II – Mitigation perform image processing*

Separating perturbations into cause and effect allow system architects to focus on what they can affect and what they can’t

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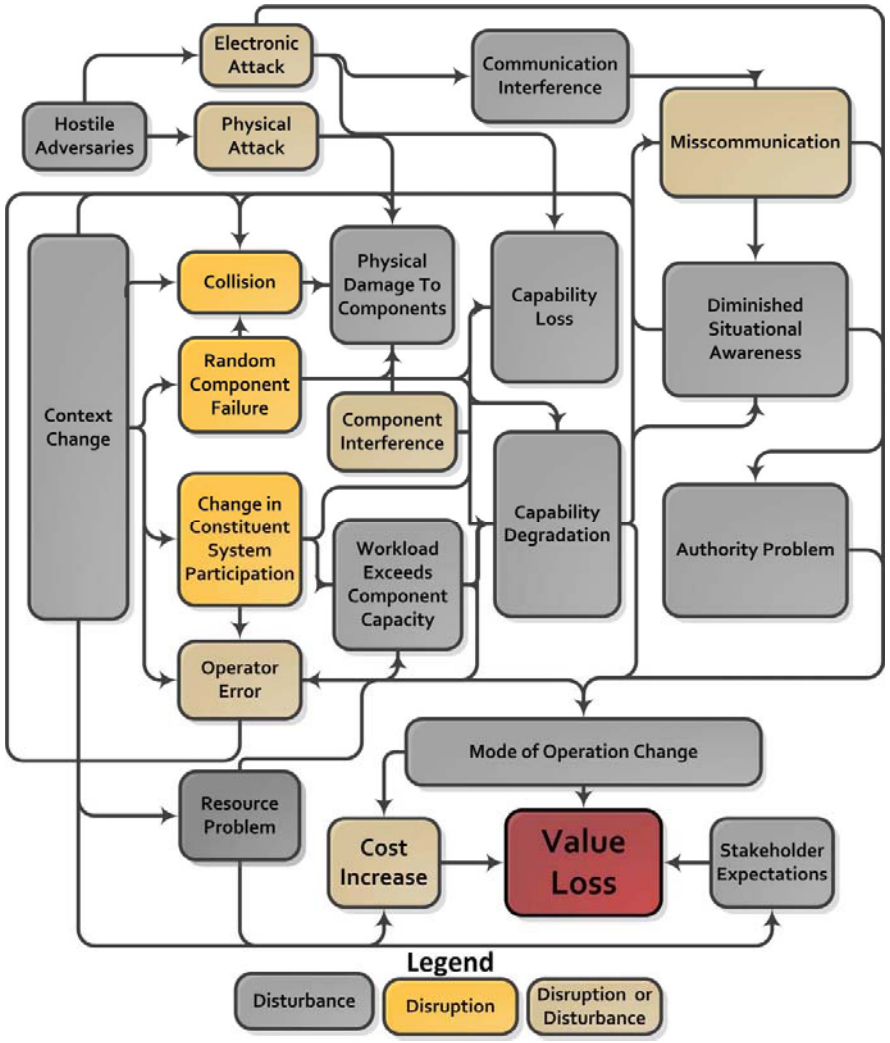
Cause and Effect Mapping



Purpose:

- To highlight the complex, non-linear relationship between causes and effects of perturbations

Method:

- Only potential perturbations that can affect the system (or for which the system can influence) are considered
- Start with an effect, determine immediate cause(s), see what other immediate effects result.
- Link existing cause/effects to each other, if appropriate

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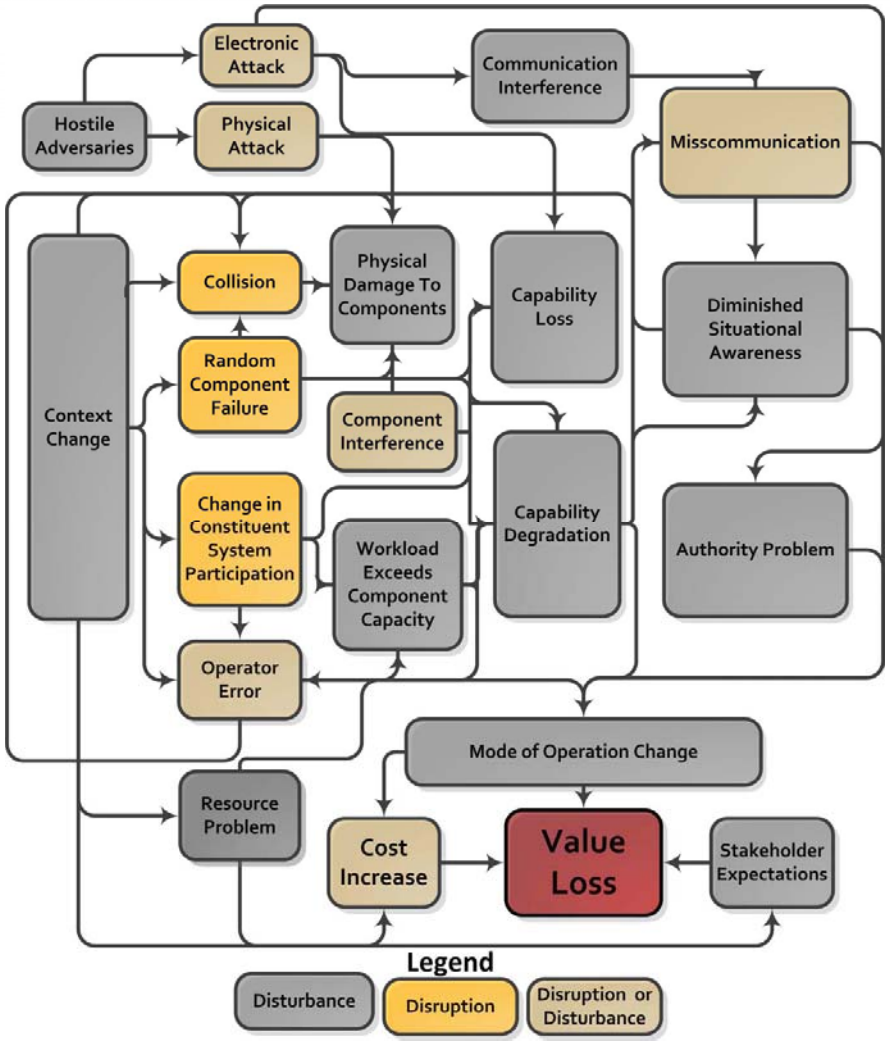
Cause and Effect Mapping



Highlights:

- Shows multiple causes / multiple effects
  - Some perturbations are more connected than others
- Exposes cascading failures
- Encourages system architects to recognize relationships that may not have been obvious
- General, rather than specific
  - Allows similar perturbations to benefit from same design principles / strategies
- Useful for broad analysis
  - FTA, FMEA/FMECA useful for specific perturbations

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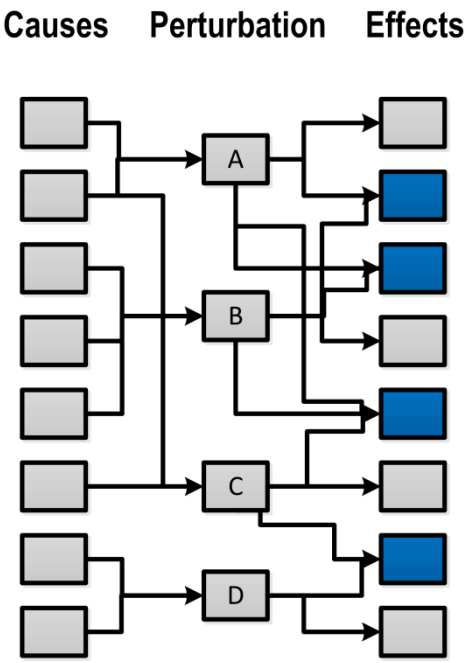
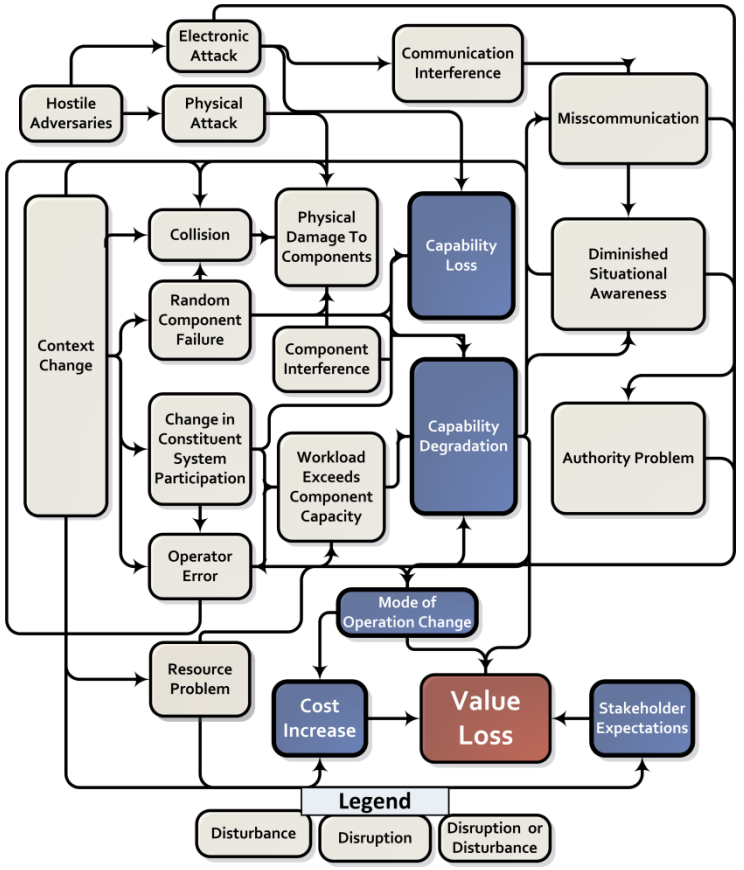
Commonalities Between Perturbations

Main Effects:

- Capability loss
- Capability degradation
- Change in mode of operation
- Cost increase
- Change in stakeholder expectation





Focusing on the main effects may yield the most useful value robustness strategies against unknown unknowns

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Example List of Perturbations, Causes, Effects and Solutions

Perturbation Example	Type	Immediate Effect	Main Effects	Causes of Perturbation	Survivability Solutions
LIGHTNING STRIKE	Disruption	Physical damage to components	Capability loss, capability degradation	Context change (weather)	Decrease cross-sectional area, divert lightning away (e.g., lightning rod)
CRASH	Disruption	Physical damage to components	Capability loss, capability degradation	Collision (caused by operator error, context change, diminished situational awareness)	Decrease cross-sectional area, increase maneuverability, increase situational awareness
FUEL PRICE INCREASE	Disruption	Cost increase	Cost Increase	Resource scarcity, mode of operation change	Store excess resource when not scarce, change to alternate resource
STAKEHOLDER CHANGES MIND ABOUT POLLUTION	Disruption	Capability loss	Change in stakeholder expectations	Context change (stakeholder)	Change components / mode of operation accordingly.
OPERATOR GIVES WRONG COMMAND TO MACHINE	Disruption	Capability degradation	Change in mode of operation	Context change (weather, bad working conditions), workload exceeds component capacity	Increase capacity (increase operators, increase automation), increase training,

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Discussion and Future Work

- Eventual goal is to develop design principles that will guide system architects to produce systems that provide value no matter what
- Working towards that goal by
  - Clarifying differences between disturbances and disruptions, so system architects can apply appropriate design principles
  - Showing how using causal chains and working backwards from value impact, systems architects can begin to determine where to intervene
  - Showing that by using cause and effect mapping, general categories of effects can be useful as a taxonomic basis, especially for dealing with known unknowns and potential unknown unknowns

Future Work:

- Apply cause and effect mapping to case studies
  - E,g. Maritime security SoS
- Use cause and effect mapping (along with other analysis methodologies) to develop survivability / value robustness strategies
- Evaluate, refine cause and effect mapping accordingly

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End of Presentation

Thank you!

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