Managing Interconnected Critical Infrastructures: Challenges to Practice and Policy

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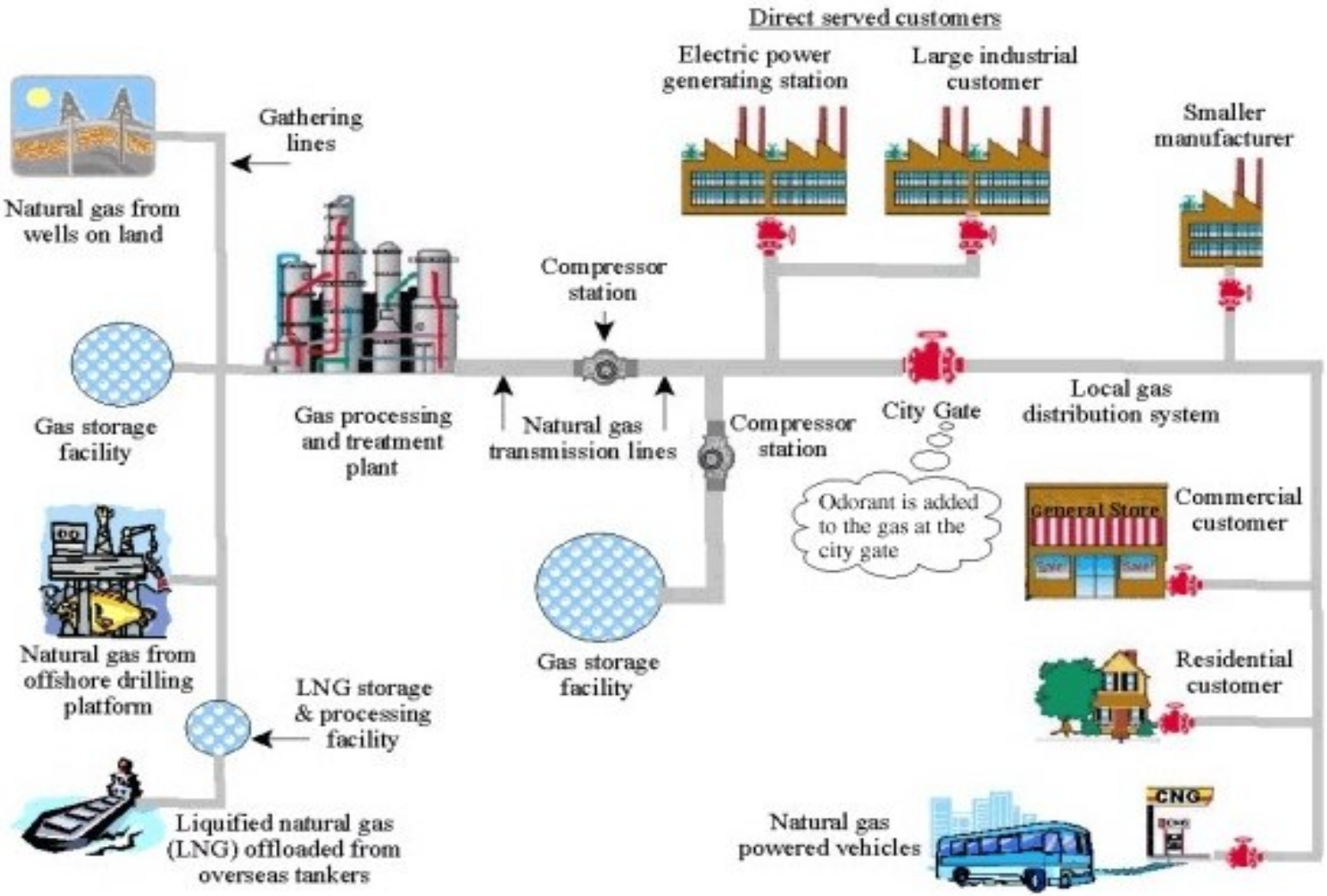
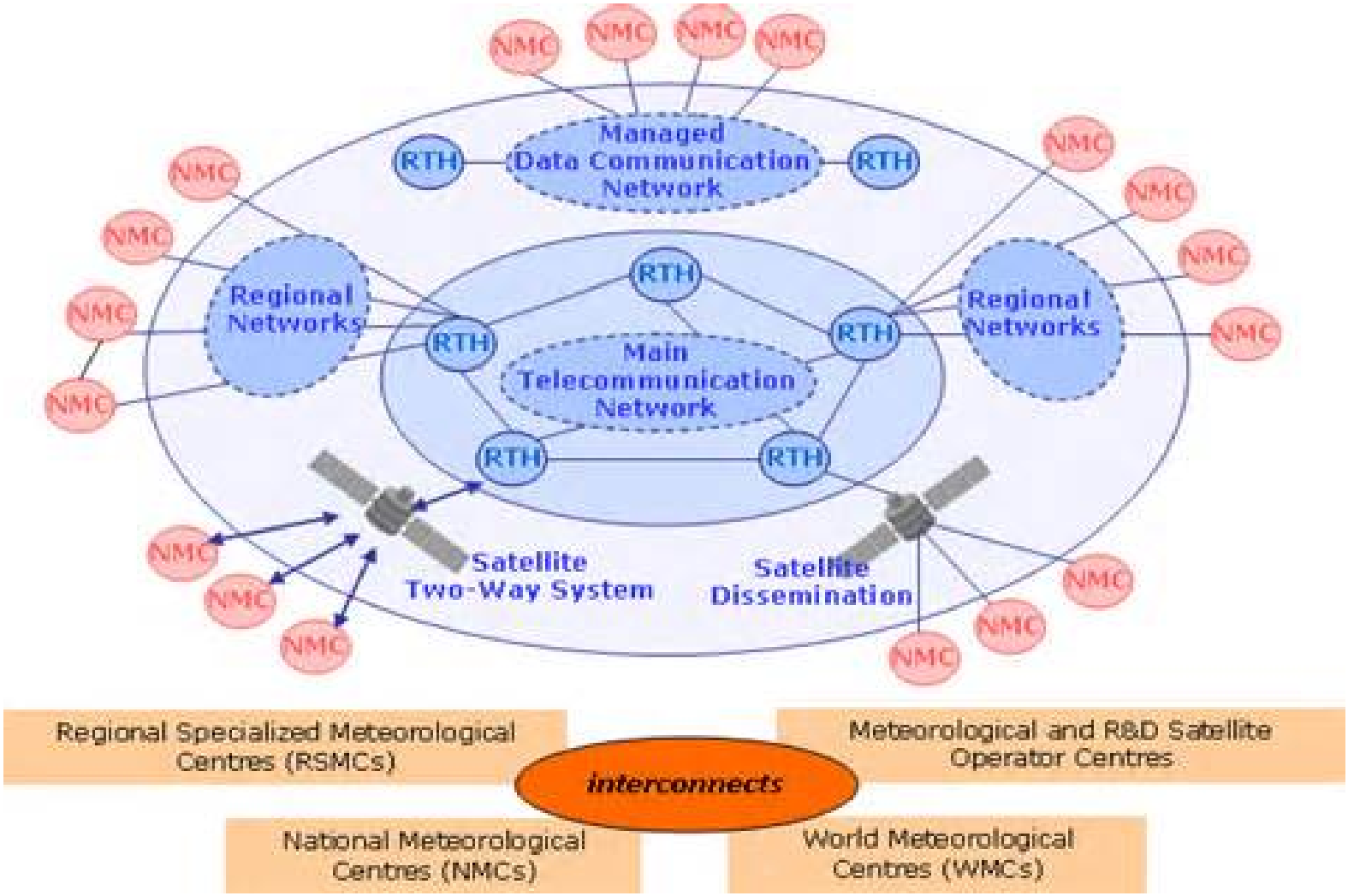
Electricity

Natural Gas

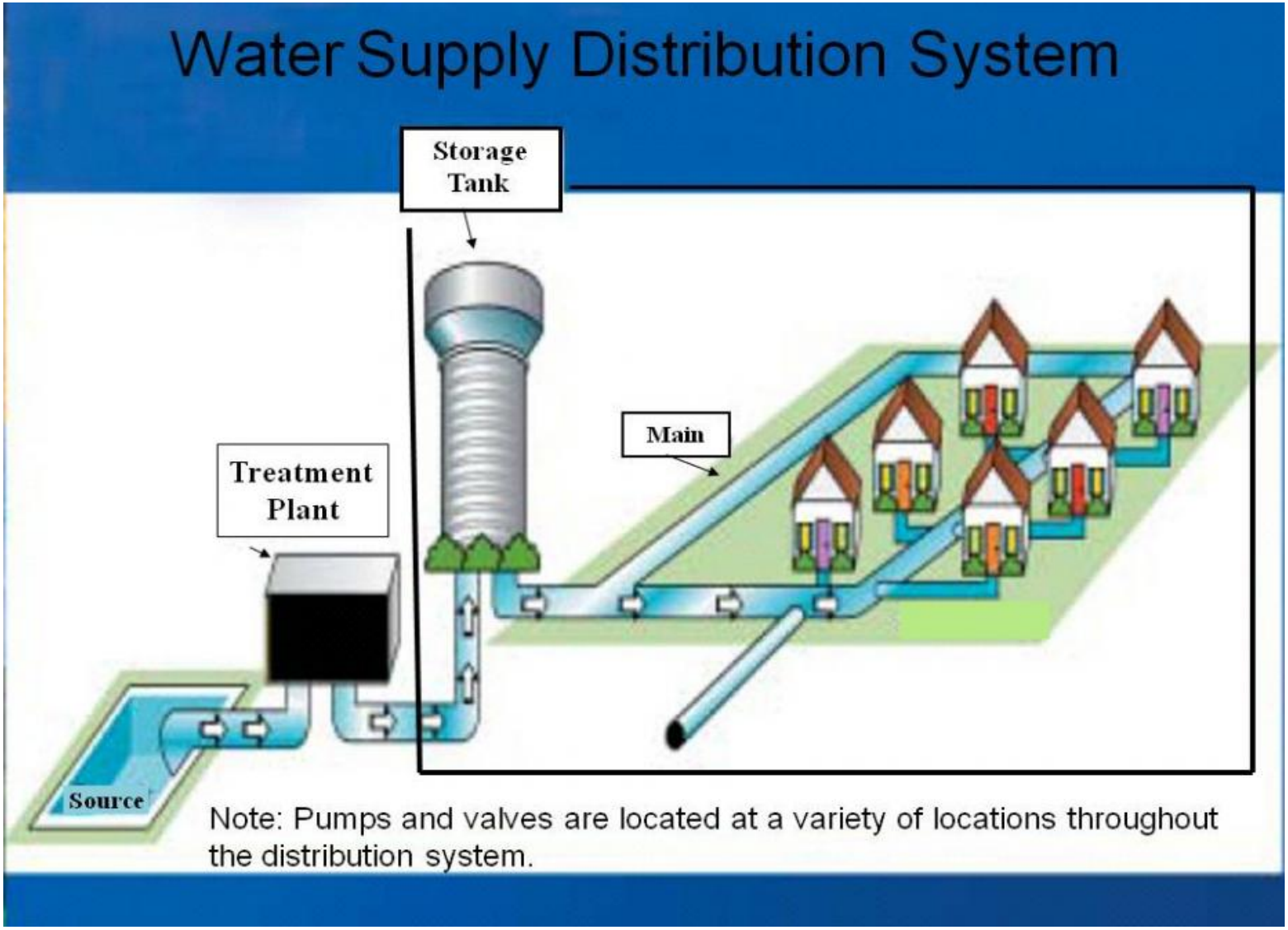

Direct served customers
Electric power generating station
Large industrial customer
Smaller manufacturer
Gathering lines
Natural gas from wells on land
Compressor station
Gas storage facility
Gas processing and treatment plant
Natural gas transmission lines
Compressor station
City Gate
Local gas distribution system
Odorant is added to the gas at the city gate
General Store
Commercial customer
Natural gas from offshore drilling platform
Gas storage facility
Residential customer
LNG storage & processing facility
Liquified natural gas (LNG) offloaded from overseas tankers
Natural gas powered vehicles
CNG

Telecommunications



Highway, rail, sea and air transport

Water supply



Levees and flood protection

These services are now defining features of the modern age

- loss of these services can in itself cause major social and economic disruptions
- their failure after hurricanes, earthquakes, floods, and tsunamis can turn these events into social catastrophes.
- infrastructure reliability – the provision and continued operation of services under widely varying conditions – is now a social and economic imperative, even considered a right

Yet the reliability of these services, among our greatest technological achievements, is increasingly uncertain.

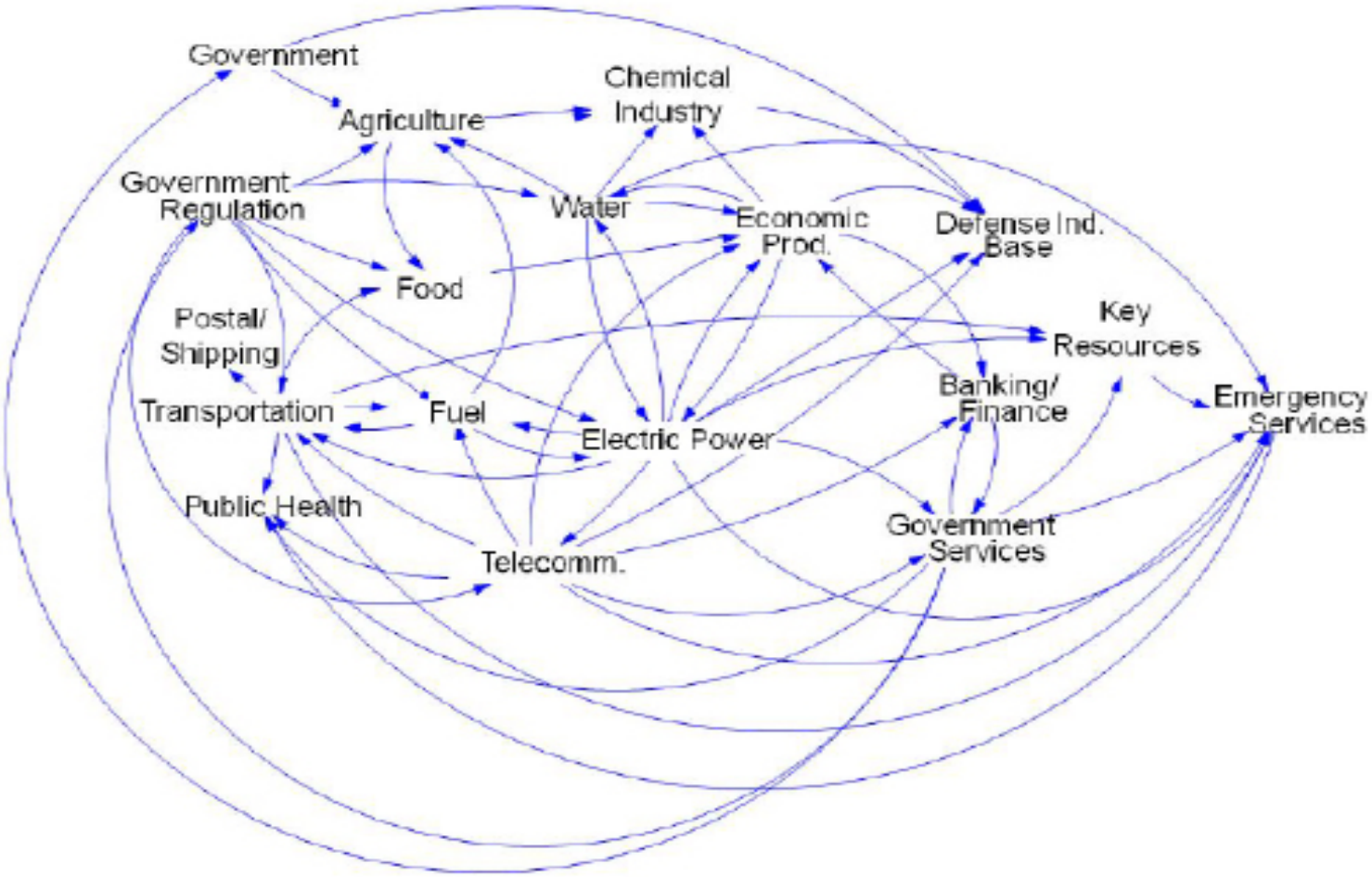
We have evolved a complex interconnectivity in these technical systems that makes their joint vulnerabilities and the risks of their mutual failure difficult to understand fully and model accurately:

- true for designers, regulators, managers even operators of these systems
- also true for risk assessors and certainly for the general public

Infrastructures “more interconnected than we can imagine”?

- The popular current approach to modeling infrastructure interconnectivity:

One Model of Infrastructure Interconnectivity



Source: Wilbanks, Fernandez, et al., 2014[8]

- Our view of these:

Incomprehensible yet *not* comprehensive

Challenges to Understanding Interconnectivity

- while conventional risk analyses consider only two conditions for infrastructures: normal operation and failure,

- in reality there are multiple performance conditions or infrastructure states:

There are at least six distinguishable states that infrastructures can assume:

- *normal operations*
- *disruption* with or without *restoration*
- *failure*
- *recovery* and
- the establishment of a *new normal*

Six different perspectives on infrastructure interconnectivity

- ICIS 1

  -- Physically proximate elements in unmanaged failure

School (lower right) adjacent to underground natural gas reservoir, which is in turn adjacent to rail line, levee and waterway on the left.

Six different perspectives on infrastructure interconnectivity (Cont'd.)

- ICIS 2

  -- Risk management of proximate elements

- ICIS 3

  -- Interconnected elements in larger managed systems (reliability beyond design)

School (lower right) adjacent to underground natural gas reservoir, which is in turn adjacent to rail line, levee and waterway on the left.

Six different perspectives on infrastructure interconnectivity (Cont'd.)

- ICIS 2

  -- Risk management of proximate elements

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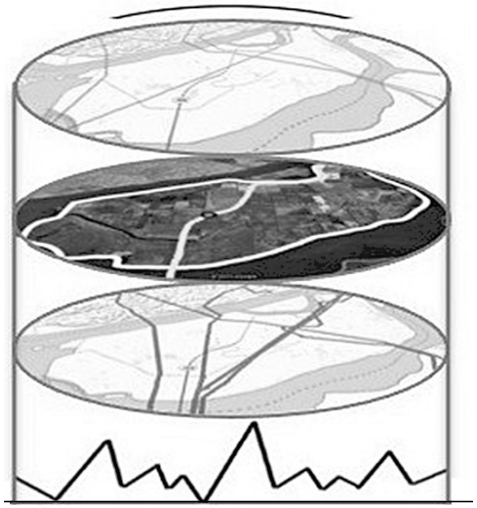
  -- Interconnected elements in larger managed systems (reliability beyond design)

ICIS 1 versus ICIS3 Perspectives on Sherman Island



Interconnectivity Perspectives (Cont'd)

- ICIS 4

  -- Same element for different infrastructure systems

- ICIS 5

  -- Different infrastructures with same control variable

  (Control variable: an actionable feature used to alter the condition or state of an infrastructure)

- ICIS 6

  -- Interconnectivity in both manifest and latent states

Types of Interconnectivity

- One-directional sequential dependency
- Bi-directional interdependency
- Mediated inter-dependency
- Pooled interdependency
- Intensive interdependency
- Contingent vs deterministic interconnectivity

Types of Interconnectivity

Sequential Interdependency:

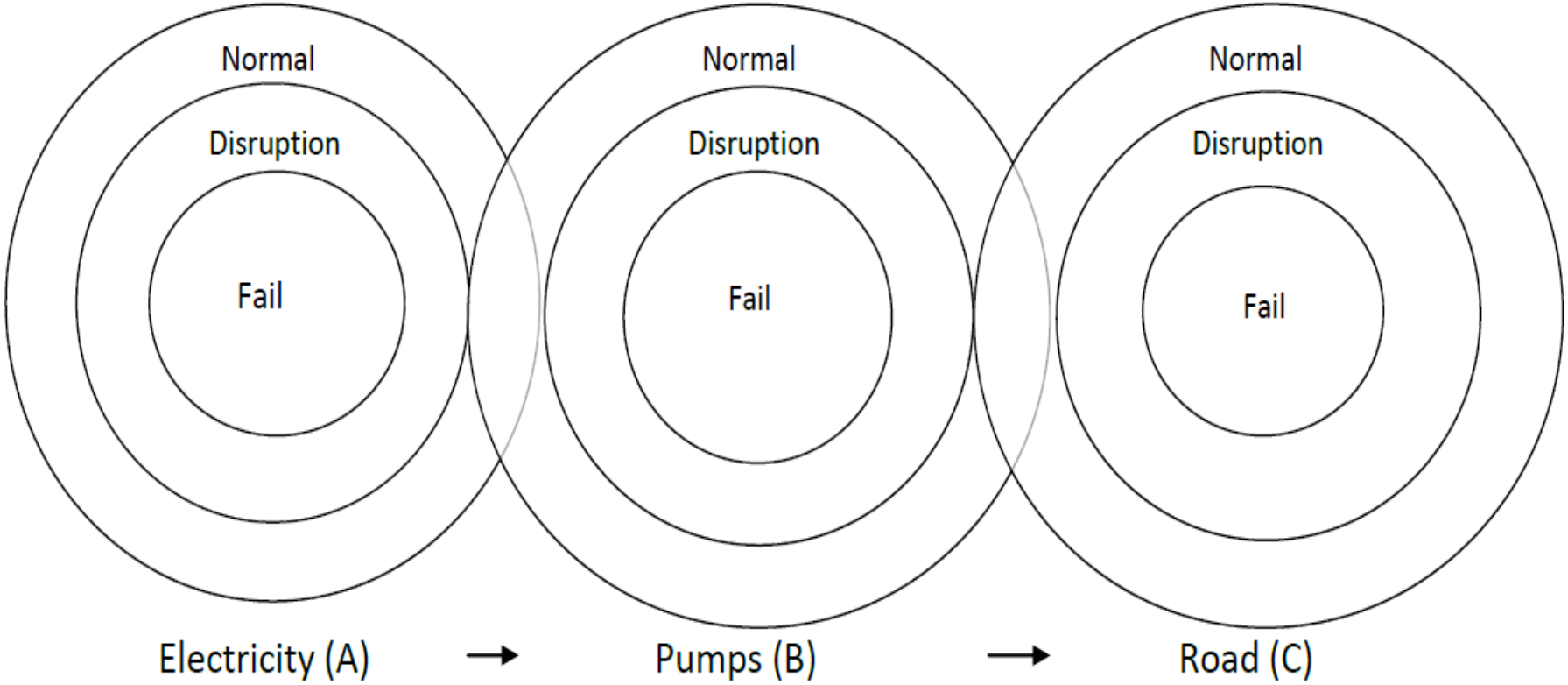


Figure 4.5 Mediated Interdependency

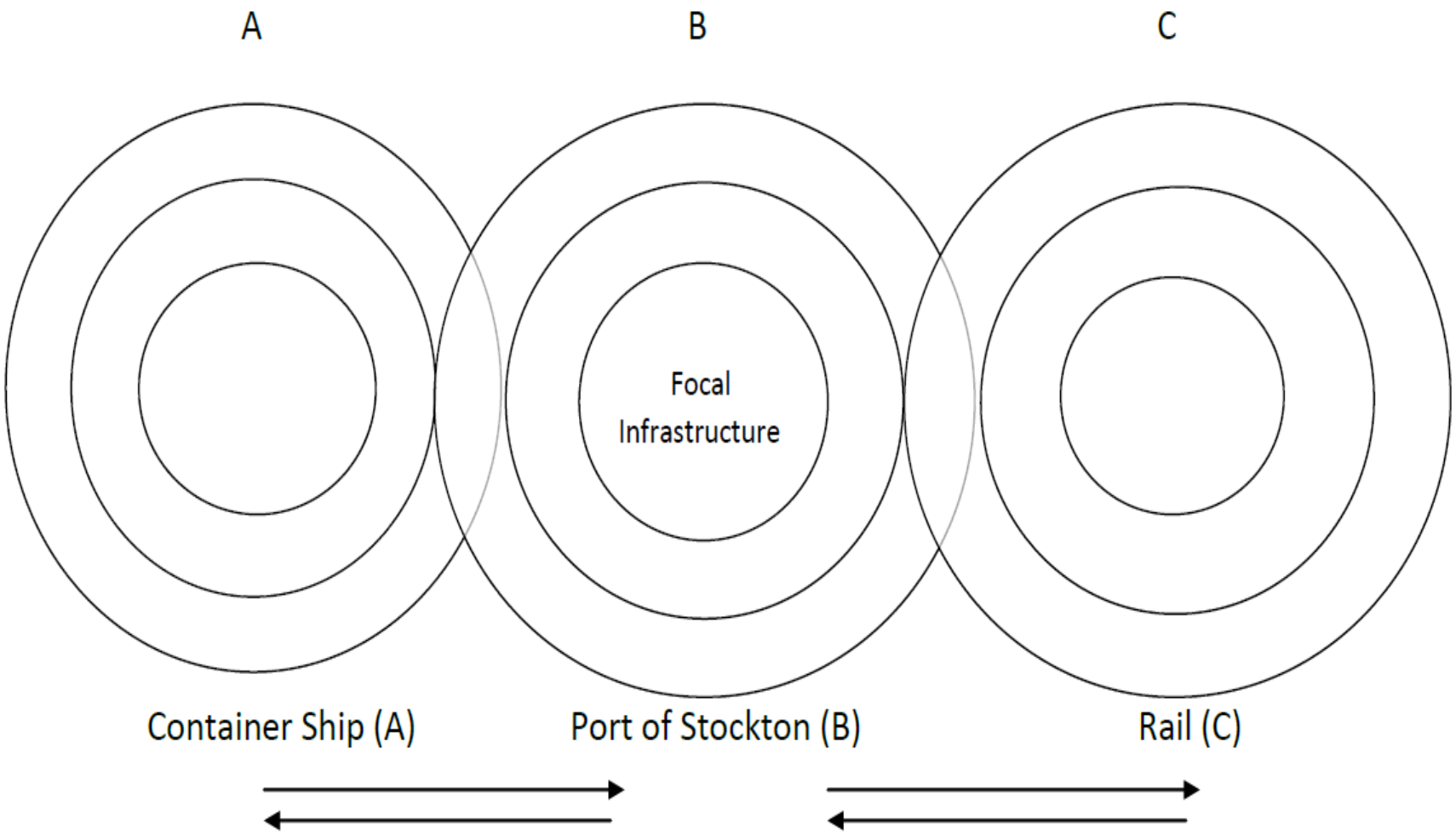
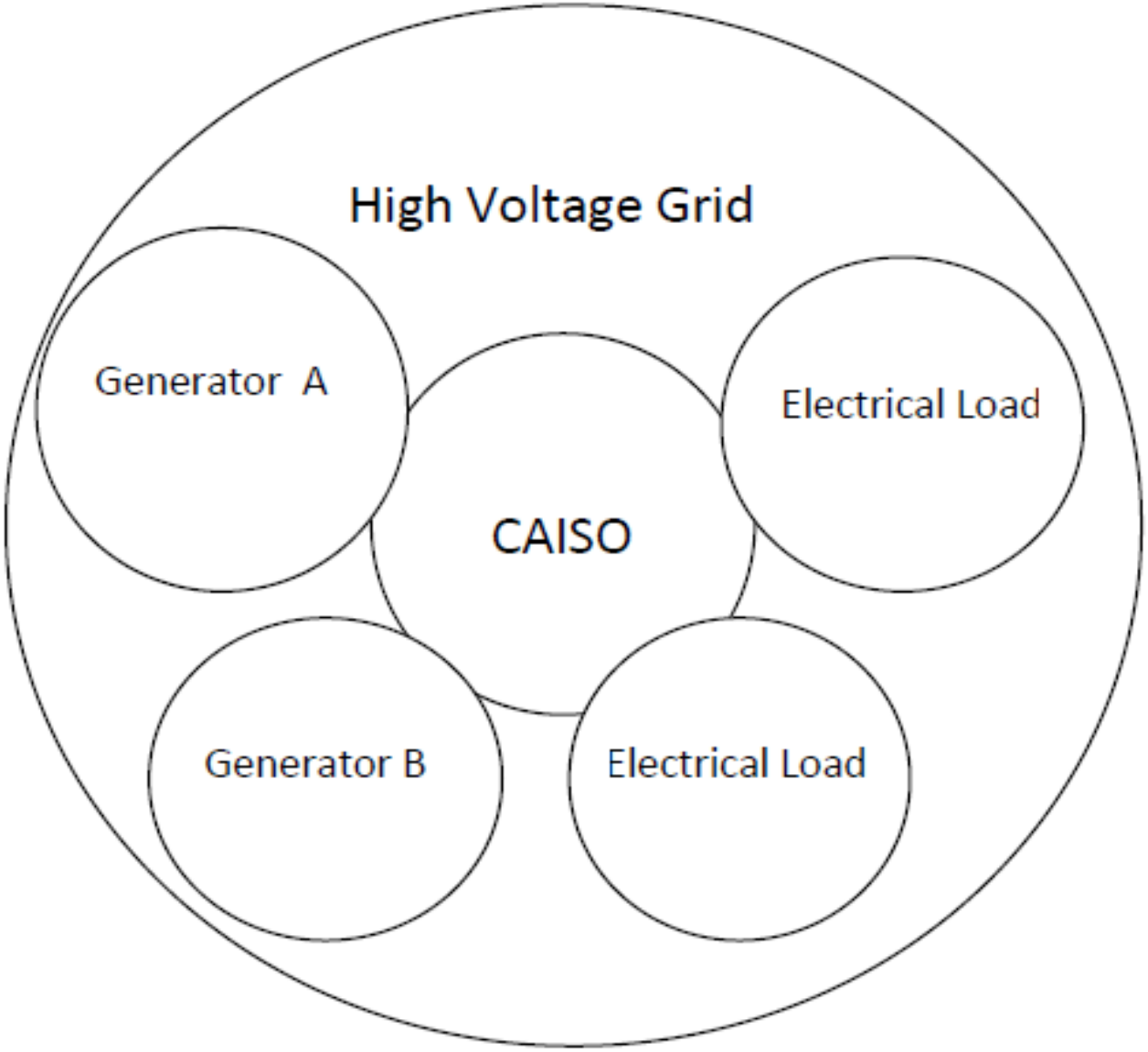
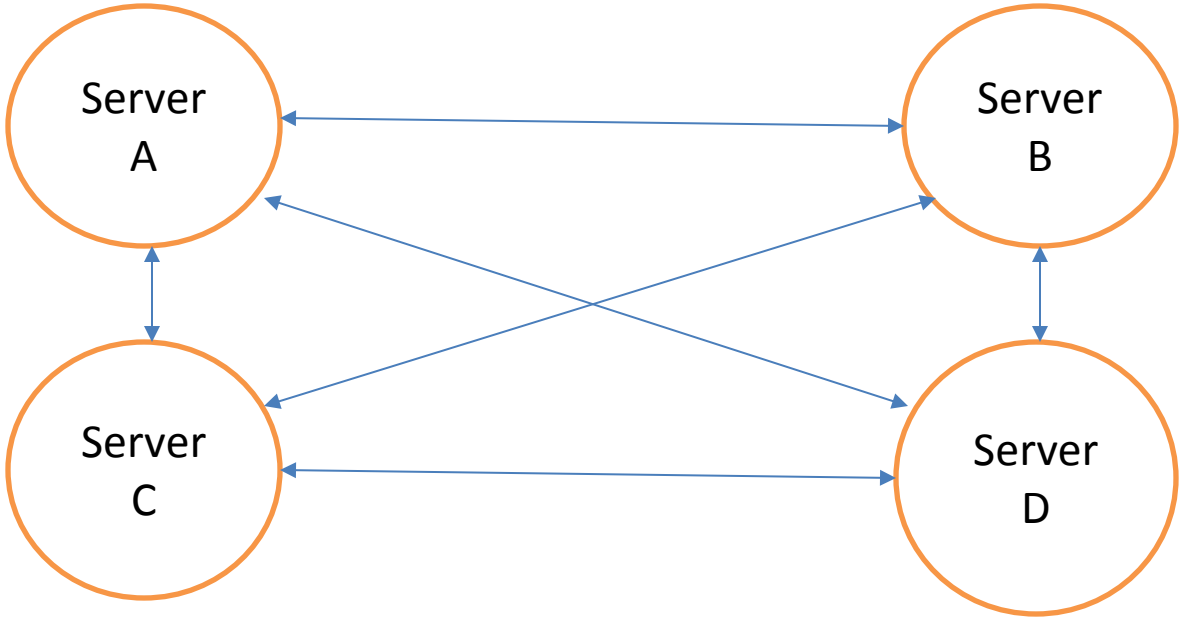


Figure 4.6 Pooled Interconnectivity



Intensive interdependency



Shift points in interconnectivity

- under *disruption* or *failure* conditions one form of interconnectivity between or among infrastructures can be transformed into another.

- the transformation means that *latent* linkages become manifest.

Interconnectivity shifts (latent to manifest)

- When their focal infrastructures are disrupted or fail, *pooled* interconnections can devolve into *bi-directional* or *intensive* interdependencies (e.g. ships must self-coordinate after VTS guidance fails).
- *Uni-directional* dependencies can become *bi-directional* interdependencies under conditions of disruption (e.g. when a levee leaks and roads and levees become functionally intertwined in flood-fighting and repair operations).
- *Probabilistic* linkages can shift into *deterministic* ones ($Cf_{CIS1} = Cf_{CIS2}$) when *pooled* interconnections become *intensive* interdependencies and collective risk becomes identical to the risk of the least reliable element.

Managerial Implications of Different Infrastructure States

- To buffer normal operations in one infrastructure from failure or disruption in another *precursor resilience* is important

  -- anticipatory reserves or redundancies

  -- identification of precursor conditions (zones)

  -- sensitivity to errors, weak signals and leading indicators

  -- deep operational experience

- To restore operation after disruption *restoration resilience* is important

  -- rapid pattern recognition

  -- rapid formulation of response options & scenarios (recognition primed decision-making)

  -- improvisation & innovation of options

  -- system perspectives combined with local actions

- Special requirements for *recovery resilience*

  -- a retreat to basics

  -- recovery as an intensive inter-infrastructural process

  -- macro and micro-coordination across infrastructures

  -- a broader scope of variables to be managed

  -- reliability tests for the “new normal”

Policy Implications of Infrastructure Interconnectivity

- Different reliability standards and strategy prevail across infrastructure states

Alternative Reliability Standards and Strategy Across Infrastructure States

Reliability Type	*Dominant Infrastructure State*	*Reliability Standard*	*Reliability Strategy*
Precluded events	Normal operations	Socially unacceptable events must not happen	Technical design, operation within analysis, precursor resilience
Avoided events	Normal, disruption, restoration	Internally unacceptable events should not happen	Risk/benefit analysis, and risk trade-offs
Inevitable events	Disruption, failure	Social acceptance of disruptions and failure as unpreventable or inevitable	Insurance, emergency response management, restoration and recovery resilience
Compensable events	Recovery, new normal	Failures forgiven by learning and added capacities in a new normal	Technology updates, procedural revision, reorganization

- Interconnected infrastructure risks as externalities
  - -- each infrastructure has to internalize costs to mitigate its risks to other infrastructures
  - -- proprietary advantages to privately owned infrastructures of withholding information about their own risks
  - -- both input and downstream reliability and risks must be weighed by each infrastructure.

Challenges to Risk Management and Policy

- New approaches needed to risk assessment
  - -- new models to cover shifting interdependencies
  - -- calculation of latent probabilities
  - -- incorporating human and organizational variables
  - -- protection against modeling away uncertainty
- New challenges to planning and regulation
  - -- planning for reliability vs reliable planning
  - -- new approaches to regulating manifest and latent interconnectivities
  - -- promotion of joint management of shared control variables
  - -- anticipation of trends and adoptions in infrastructure technology

Further conversations

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