Classifying Emergent Behavior to Reveal Design Patterns

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Motivation

- Emergence is used in many domains
  - Science, Engineering, Philosophy, Biology, etc.
- Often more theoretical than applied
- Goal is an organized, application-oriented typology to be used for
  - Problem-solving
  - Reference
  - Education
- Would result in better preparation (though not prediction) for emergence

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Nomenclature

- Classification: generic organization by some metric
- **Typology**: Classification with multiple, simultaneous means of division
  - Theocratic, authoritarian government == Authoritarian, theocratic government
- Taxonomy: Classification with multiple consecutive means of division
  - Homo sapiens =/= Sapiens homo

(Marradi, 1990)

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What is Emergence?

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Definitions

- In this presentation, **emergence / emergent behavior** refers to behavior
  - As opposed to complexity which often (not always) refers to the system, rather than a behavior
  - Complex systems often exhibit emergent behavior
- The behavior can be described as seemingly organized/unified macro-scale or systems-level behavior that is actually the combined result of micro-scale or component-level behavior.
- SEBoK: “System wholes have behaviors and properties arising from the organization of their elements and their relationships.”

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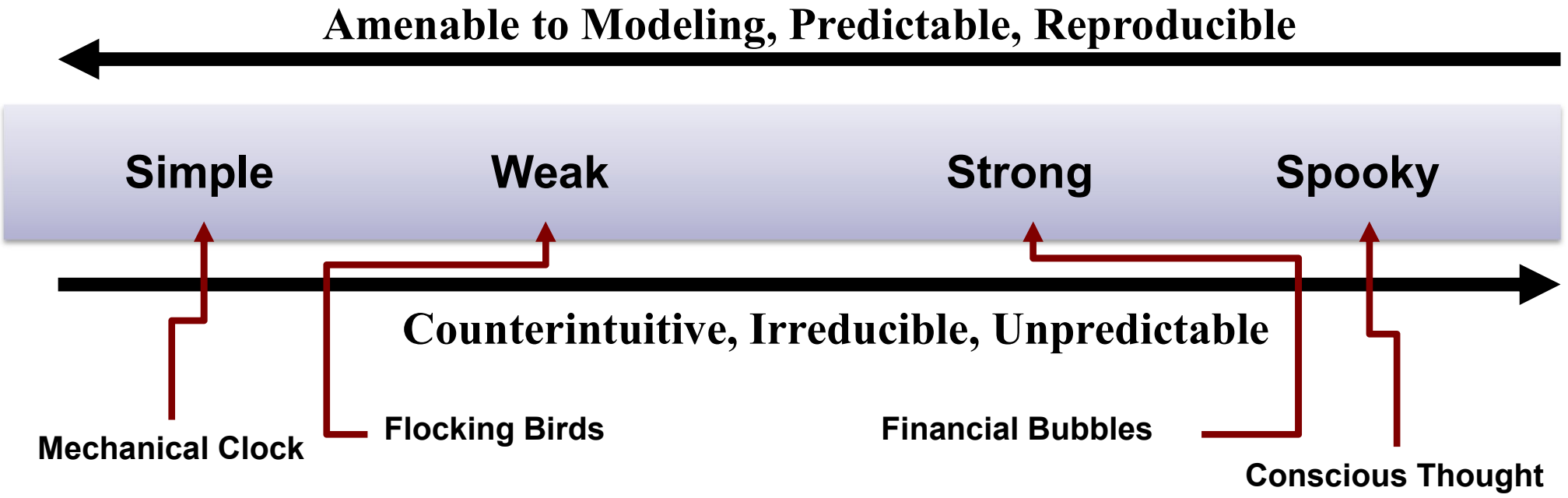
Model-ablility

- Categorization focuses on how reducible and simulatable it is (Bjelkemyr, 2008)
- One phenomena could potential move to the left as it becomes better understood



(Maier, 2015)

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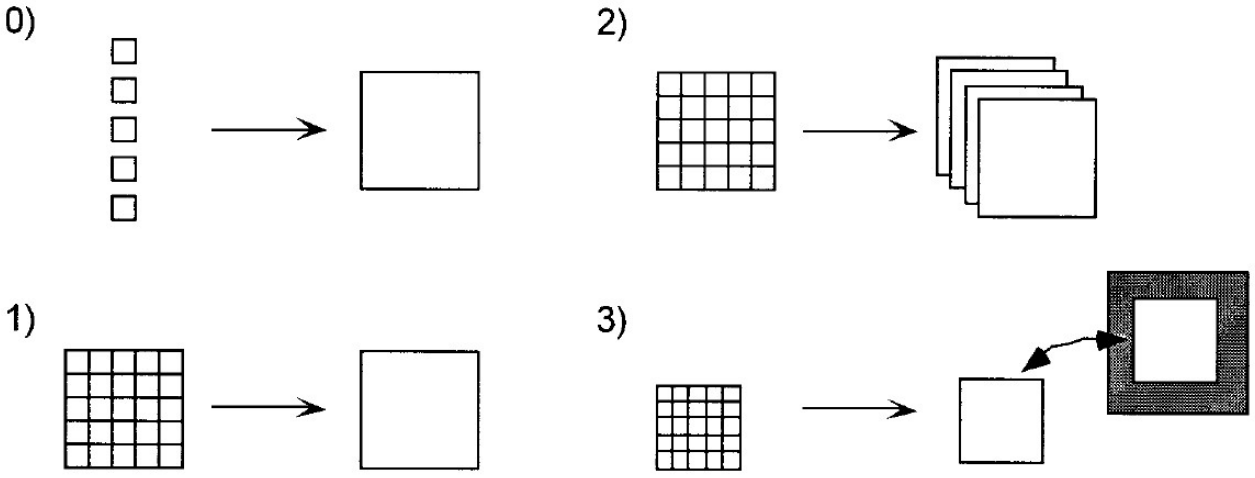
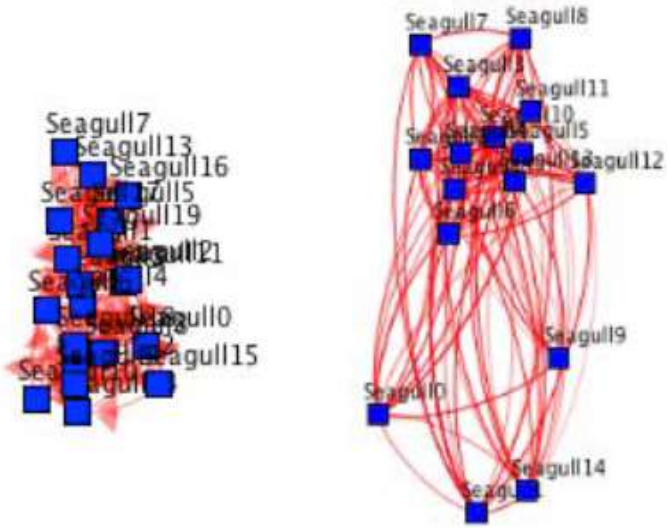
Interaction

- Either qualitative or quantitative
- Based on the number and types of component interfaces
- Emergence is the behavior found in the difference between the sum of component states and the set of system states



(Bar-Yam, 2004)



(Szabo, 2014)

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Expressed Behavior

- Descriptive, based on form of behavior rather than cause

Behaviour Types	Description	Examples
Thrashing	When competition over a resource results in switching costs between the sharing parties dominate actual useful work	Computers when insufficient working memory is allocated for the task at hand, a notable instance of this was the IBM/370 mainframe computers
Synchronization	When components who time-varying behaviour normally is uncorrelated becomes correlated.	The frequency of pedestrians steps on the London Millennium footbridge, router protocol message synchronization
Livelock	When progress stalls because multiple components keep adjusting in such a way as to remain counteracting one another	Two individuals “dancing” in a hallway while trying to get around one another, Ethernet Capture Effect

(Mogul, 2006)

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Design Patterns

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Definitions

- Design Principle: Abstract rule that produces concrete solutions to design problems
- Design Heuristics: The other subset that are more general, largely aimed at design process
  - "80-20 Rule," "measure twice, cut once"
- Design Patterns: Subset aimed at specific problems and apply to the design itself (rather than the process)

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Example

Name	Margin
Type	Operational
Design Principle	Margin (Jackson, 2012; Richards, 2009)
Problem	Capability is not being provided adequately.
Context	Perturbation causes the output of system to be inadequate.
Solution	Have system be capable of producing more output than necessary.
Unintended Consequences	May add require additional components, meaning unnecessary size (reducing the strategy of miniaturization), and/or unnecessary weight (making the strategy to mobility difficult to achieve).
Example	Extra-long wings on an A-10 aircraft, which generates enough lift in the event that part of the wings are destroyed or damaged.
Related Patterns	Heterogeneity, Physical Redundancy

(Mekdeci, 2013)

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Typology to Design Patterns

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Causal Factors

- Emergent behavior typically does not have “a cause” but rather contributing factors

Causal Factor	Explanation	Examples
Density	As the energy or material density of a system increases, feedback loops are accelerated and strengthened, nonlinear behavior becomes more apparent, and likelihood of a perturbation increases.	Spontaneous Traffic Jam; Laminar vs Turbulent fluid flow; Locust Swarms; PsEPR herding
Frequency Matching	Two or more known feedback loops or oscillations that were expected to have different frequencies are instead found to have mutually reinforcing frequencies.	Vortex Induced Vibration, London Millennium Footbridge Vibration
Perturbation / Nucleation Site	There exists some temporally and spatially limited variation to input to the system, either endogenous or exogenous, that can agitate local nonlinearities, potentially initiating a chain-reaction across the system	Financial Market Crash; Power Grid Cascading Failure; Laminar vs Turbulent fluid flow; Spontaneous Traffic Jam;

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Causal Factors

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Example Typologies

Emergent Behavior	Synchronization	Phase Change	Oscillation
Description of Emergent Behavior	Components of the system or of the environment whose time-varying behavior is expected to be uncorrelated become correlated	The system switches between two or more states in an irregular, unintended, or irreversible way	The system or some set of components periodically switch back and forth between two or more states in some repeating pattern.
Consequences	Can increase the load on a component or the system as a whole, alternately may result in greater efficiency of a system that is normally random	Can cause the system to act in unpredictably, making control and monitoring more difficult. Can also dramatically increase or decrease system performance.	The rapid state changes can inhibit productive function or cause undue loading to some parts of the system.
Common Causal Factors	Unexpected Inputs; Decentralized Control; Frequency Matching; Unexpected Feedback Loops, Density	Density; Perturbation/Nucleation Site	Unexpected Feedback Loops, Frequency Matching
Suggested Action(s) to Alleviate	Over Design Capacity; Induce Randomness; Introduce Perturbations	Remove Perturbations; Over Design for Capacity	Decoupling; Induce Randomness
Suggested Action(s) to Encourage	Minimize Perturbations; Market-Based Control; Gradient Fields	Induce Perturbations; Add Energy	Introduce Time Delays
Example	Frequency of pedestrian steps on the Millennium footbridge; router protocol message synchronization; PsEPR herding; Laminar fluid flow	Spontaneous Traffic Jam; Laminar vs Turbulent fluid flow; Cascading Network Failure; Locust Swarms	Vortex Induced Vibration, London Millennium Footbridge Vibration; PsEPR herding; Gliders in Conway's Game of Life

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Example Typologies

Emergent Behavior	Synchronization
Description of Emergent Behavior	Components of the system or of the environment whose time-varying behavior is expected to be uncorrelated become correlated
Consequences	Can increase the load on a component or the system as a whole, alternately may result in greater efficiency of a system that is normally random
Common Causal Factors	Unexpected Inputs; Decentralized Control; Frequency Matching; Unexpected Feedback Loops, Density
Suggested Action(s) to Alleviate	Over Design Capacity; Induce Randomness; Introduce Perturbations
Suggested Action(s) to Encourage	Minimize Perturbations; Market-Based Control; Gradient Fields
Example	Frequency of pedestrian steps on the Millennium footbridge [22]; router protocol message synchronization [23]; PsEPR herding [19]; Laminar fluid flow

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Design Pattern

Over Design Capacity / Increase Capacity	
Emergent Behavior Types Addressed	Synchronization; Phase Change
Context	Emergent behavior, potentially exacerbated by the material or energy density in the system, results in higher than expected load on some component or the system as a whole
Action	Allow for extra load capacity than would be necessary should no emergent behavior occur.
Unintended Consequences	May result in induced demand; will likely require additional resources (particularly physical space) that may be costly or not be available
Example	Increased memory capacity resulted in trashing behavior like that seen in the IBM/370 become less common [21]; opening the shoulder of a highway as an additional lane can (at least temporarily) reduce traffic [37]
Related Patterns	Margin, Heterogeneity, Physical Redundancy

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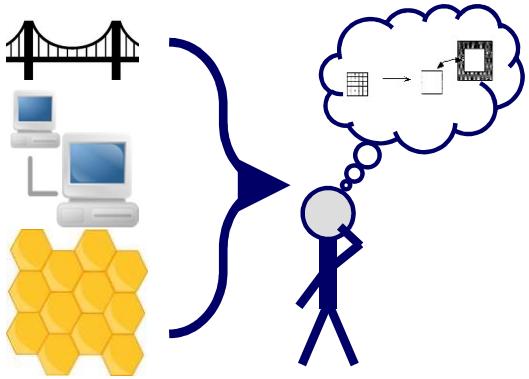
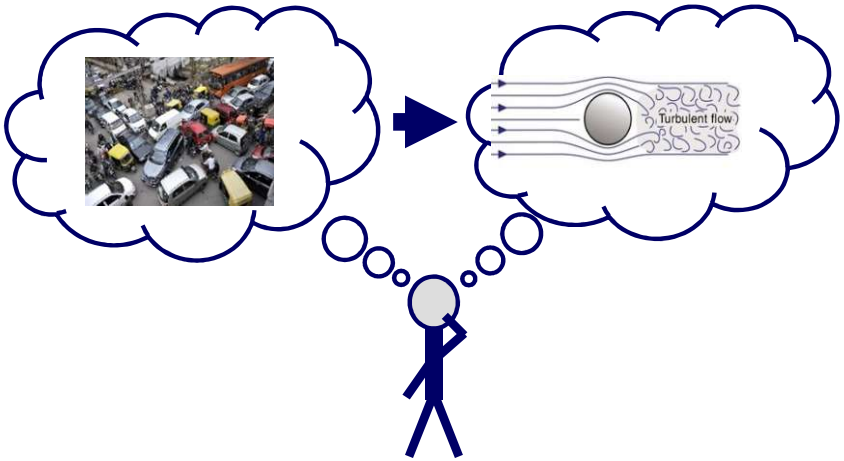
Uses

Initial introduction to emergence



Reference source for problem solving



Documentation hub

Naming and Description			Type of System			Categorization			
System	Description of Behavior	ion Remedies/Induc	Origin	Tags	Beneficial	Bjelkemyr (2008	Bedau (2002)	Bar-Yam (2004)	Gore (2007)
Brain	Consciousness	N/A	Natural	evolved, neural, network, biology, h	Yes	Strong	Weak/Strong	Type 3	Stochastic, Unpredictable, Manifes
Conway's Game of Life	Simple "live-or-die" rules results in compl	?	Artificial	designed, artificial biology, disease	Yes	Weak	Nominal	Type 2	Deterministic, Predictable, Materia
Starling Flock	Following simple neighbor-to-neighbor ru	N/A	Social	evolved, group, swarm	Yes	Weak	Nominal	Type 1	Stochastic, Predictable, Manifested
Ant Colony	Ants follow basic rules and use simple sti	N/A	Social	evolved, group, swarm, algorithm	Yes	Weak	Nominal	Type 1	Stochastic, Predictable, Manifested
Locust Swarm	Transition from solitary grasshopper pha	To Prevent: Prevent	Social	evolved, group, stressor, tipping po	Yes	Weak	Nominal	Type 1	Stochastic, Predictable, Manifested
Diffusion	Diffusion is an emergent phenomena fron	N/A	Natural	micro, macro, stoichastic, physical	Neutral	Weak	Nominal	Type 1	Stochastic, Predictable, Manifested
Stock Market Bubble	Momentum, groupthink, and speculation	?	Social	economic, groupthink, momentum,	No	Weak	Nominal	Type 2	Stochastic, Unpredictable, Material
High Frequency Trading Crash	Similar to Stock Market Bubble, but occu	?	Artificial	economic, algorithm, computer, tipp	No	Weak	Nominal	Type 2	Stochastic, Unpredictable, Material
Millennium Footbridge Vibration	Small, harmless oscillations of bridge re	?	Social	synchronization, infrastructure, osc	No	Weak	Weak	Type 3	Deterministic, Unpredictable, Mani
Tacoma Narrows Bridge Oscillatio	Lift due to wind and lack of torsional stal	?	Artificial	oscillation, infrastructure, transpo	No	Weak	Nominal	Type 2	Deterministic, Predictable, Manifes
Spontaneous Traffic Jam	In high traffic areas, a momentary stutter	?	Social	infrastructure, transportation, shoc	No	Weak	Nominal	Type 2	Stochastic, Predictable, Materializi
Inter-Disk Vibration	The vibration of one harddrive's seek act	?	Artificial	computer, oscillation, interference,	No	Weak	Nominal	Type 3	Deterministic, Unpredictable, Mani
Ethernet Capture Effect	If two LAN hosts simultaneously try to se	Changed protocol such	Artificial	algorithm, oscillation, computer	No	Weak	Nominal	Type 1	Stochastic, Predictable, Materializi
Router Synchronization	Routers that periodically exchange routir	inject a sufficiently lar	Artificial	synchronization, algorithm, comput	No	Weak	Nominal	Type 2	Stochastic, Unpredictable, Material
Route Flap Damping in BGP	In sufficiently large networks, the protoc	?	Artificial	algorithm, computer	No	Strong	Weak	Type 3	Stochastic, Unpredictable, Material
TCP's Nagle Algorithm		?	Artificial		No				
Fish School	Mimicry and dodging	N/A	Social	evolved, group, swarm, macro, mar	Yes	Weak	Nominal	Type 1	Stochastic, Predictable, Manifested
PqDPR Herding	In a particular propogation system, clien	Instead of sending a fu	Artificial	synchronization, oscillation, algori	No	Weak	Nominal	Type 1	Stochastic, Predictable, Materializi
Mars Pathfinder Priority Inversior	Due to better than expected data transfer	Software updated that	Artificial	resource, algorithm, computer	No	Weak	Nominal	Type 2	Deterministic, Predictable, Manifes
Development of Popular Hashtags	Many new hashtags are constantly being	?	Social	popularity, feedback, social media,	Yes	Strong	Weak	Type 3	Stochastic, Predictable, Materializi
Jet Stream	Macro-structure wind patterns that resul	N/A	Natural	weather, macro,	Neutral	Weak	Nominal	Type 2	Stochastic, Predictable, Materializi
El Niño	Periodic warmer waters off the coast of S	?	Natural	weather, macro, marine, oscillatior	Neutral	Strong	Weak	Type 3	Stochastic, Unpredictable, Manifest
Parallel Cooling Pumps Restarting	One pump (pump A) will invariably have	?	Artificial	flow, oscillation, resource, mechan	No	Weak	Nominal	Type 1	Deterministic, Predictable, Materia
Artificial Neural Networks	After being fed large amounts of training	?	Artificial	computer, algorithm, neural, netwo	Yes	Strong	Weak	Type 3	Deterministic, Unpredictable, Mani
Protein Folding	The shape of a given hypothetical protein	?	Artificial	microbiology, chemical, biology,	Yes	Strong	Weak	Type 3	Deterministic, Unpredictable, Mani
Agent-Based Models	Simulation wherein individual component	?	Artificial	computer, model, algorithm, group	Yes	Weak	Nominal	Type 2	Stochastic, Unpredictable, Manifest
Mechanical Watch	Individual gears and springs each perfor	?	Artificial	oscillation, mechanical, simple	Yes	Weak	Nominal	Type 0	Deterministic, Constant, Manifeste
Internet	Individual computers connect via the TCP	?	Artificial	infrastructure, computer, algorithm	Yes	Strong	Weak	Type 3	Stochastic, Unpredictable, Material
Aggregate Supply & Demand	Individuals willingness to buy or purcha	?	Social	economic, synchronization, human,	Neutral	Weak	Nominal	Type 2	Stochastic, Predictable, Materializi
Arab Spring	A combination of a variety of factors incl	?	Social	economic, human, tipping point, gr	Neutral	Strong	Weak	Type 3	Stochastic, Predictable, Materializi
Zebra Stripes	Pigment cells operate on a combination c	?	Natural	evolved, feedback, cellular, microb	Yes	Weak	Weak	Type 2	Stochastic, Predictable, Manifested
Stock Market Typical Behavior	Individuals' assessment of the value of st	?	Social	economic, feedback, group, tipping	Neutral	Strong	Weak	Type 3	Stochastic, Predictable, Materializi
Scientific Revolution	Science operates on a fairly simple set of	?	Social	groupthink, tipping point, populari	Yes	Strong	Weak	Type 3	Stochastic, Unpredictable, Material
Life	Life itself is an emergent behavior of a se	?	Natural	biology, chemical, feedback	Yes	Strong	Weak/Strong	Type 3	Stochastic, Unpredictable, Manifest
Culture	Culture is built upon individuals' actions	?	Social	groupthink, popularity, human, ma	Neutral	Strong	Weak/Strong	Type 3	Stochastic, Unpredictable, Manifest
Robot Swarm	Individual robots are programmed to per	?	Artificial	swarm, group, computer, controls,	Yes	Weak	Weak	Type 3	Deterministic, Predictable, Manifes
Power Grid Cascading Failure (20	Random transacations, perturbations, ar	Homogenous "fish-net"	Artificial	infrastructure, electricity, network,	No	Weak	Nominal	Type 2	Deterministic, Predicable, Material

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Moving Forward

- Collect further types of behavior, causal factors, suggested actions, and examples
  - Suggestions are welcome!
- Imagined to ultimately be on scale of dozens of types of behaviors
  - Similar to ilities
- Experiment with educative/reference potential

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Preliminary Cross-Listing

Suggested Actions to Alleviate	Common Causal Factors					
	Density	Perturbation / Nucleation Site	Unexpected Feedback Loops	Frequency Matching	Unexpected Inputs	Decentralized Control
Over Design Capacity (Margin)	Synchronization		Synchronization	Synchronization	Synchronization	Synchronization
Induce Randomness	Synchronization		Synchronization Oscillation	Synchronization Oscillation	Synchronization	Synchronization
Induce Perturbations	Synchronization Phase Change	Phase Change	Synchronization Oscillation	Synchronization Oscillation	Synchronization	Synchronization
Decoupling				Oscillation		
Remove Perturbations	Phase Change	Phase Change				

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Questions?

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