Comparing Principles of Robustness in Biological and Socio-Technical Systems

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Summary

Robustness is an important property of socio-technological systems operating in dynamic and uncertain environments. Although terminologies differ greatly, the mechanisms and principles known to support robustness are surprisingly similar to those observed in biological systems. Here we discuss recent developments in understanding biological robustness and we propose important and thus far overlooked principles that could further enhance the robustness of socio-

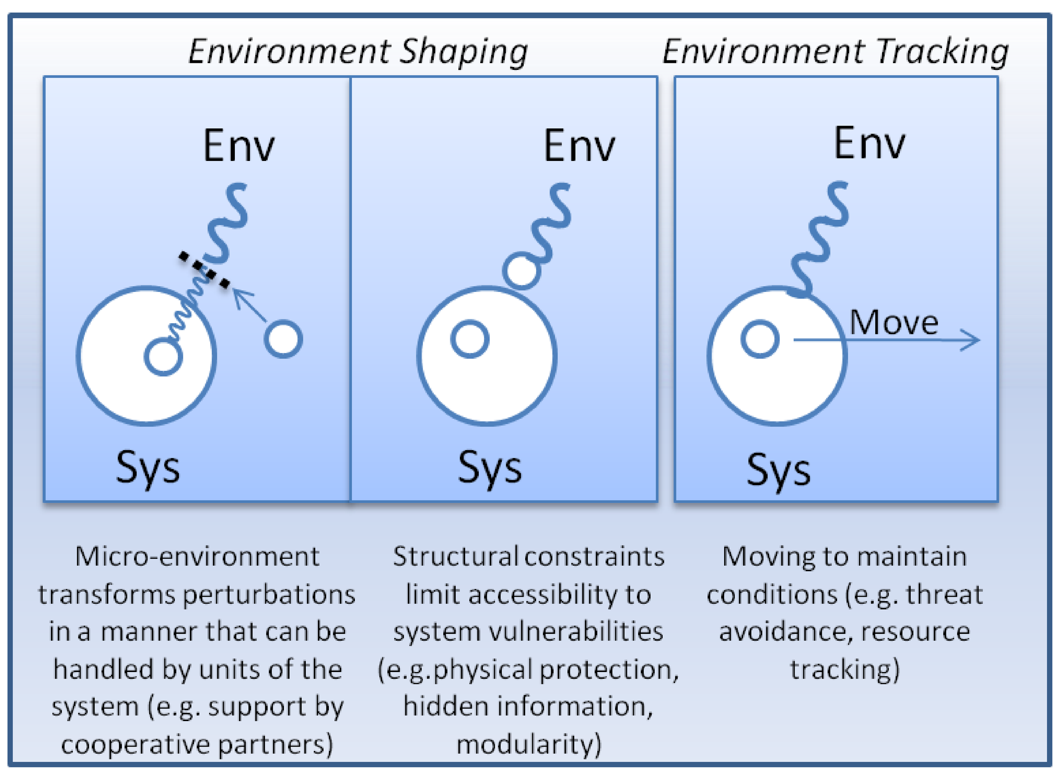
Our Proposal

We propose that a biological property known as degeneracy can support several types of adaptation that are important to sociotechnical systems, while also improving efficiency over bet-hedging and redundancy paradigms.

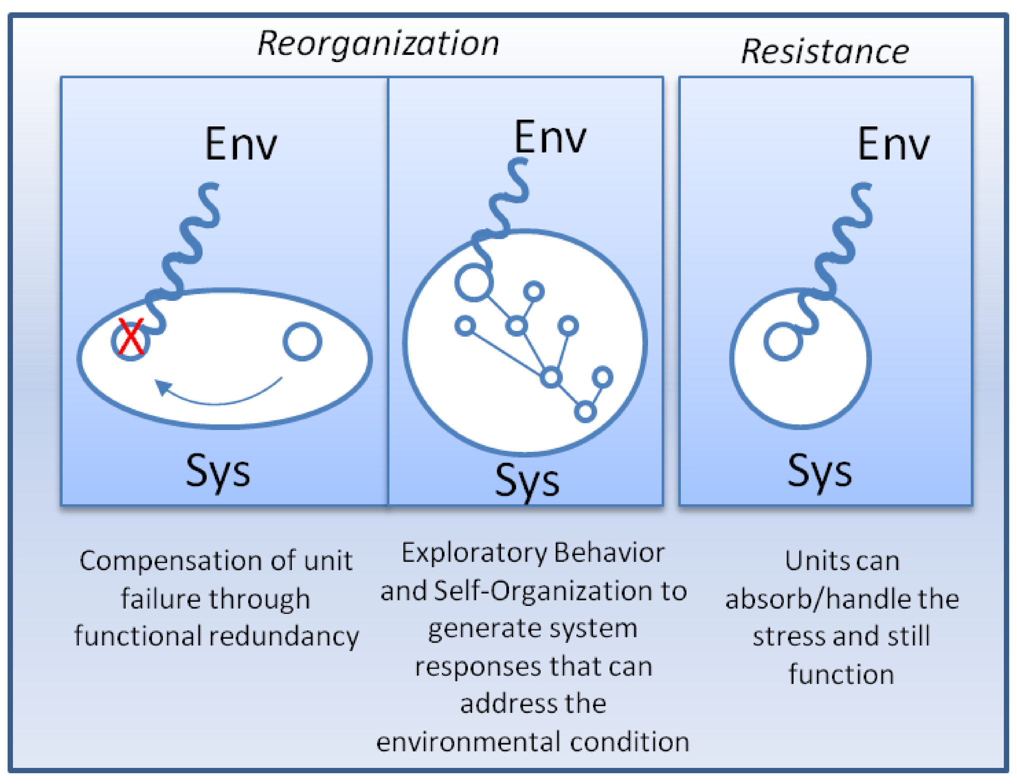
Intro: There is a small set of basic principles that support robustness in many complex systems, e.g. ecosystems, biochemical networks, systems engineering, and human organizations .

Mechanisms that enhance robustness	Biological Examples	Engineering and Management Examples
Reliability through functional and pathway redundancy		
distinct components or pathways that are interchangeable and thus robust against the loss of a single component	Gene regulation, protein functionality, metabolic and signalling pathways, and neural anatomy often display high levels of functional redundancy.	Empirically driven placement of backup devices as well as storage/maintenance/ preservation facilities can buffer against fluctuating operating conditions .
Resistance		
robustness of component towards variable conditions removes need for any system level adaptive response	Many types of threshold effects in biology appear as sub-systems with innate (but bounded) resistance to change (e.g. Genetic switches, TCR mediated activation of T cells, neural activation)	High cost ultra-quality components with lower rates of failure can provide reliability in circumstances where replacement is impractical.
Local environment shaping /regulation		
Instead of achieving robustness by responding to environmental stress, it is sometimes possible to shape the environment in ways that allow a system to avoid exposure to damaging stress	Niche construction and environment simplification alter the type and frequency of perturbations encountered. Heat shock proteins (e.g. Hsp90) assist other proteins to fold and refold into functionally relevant conformations and confer conformational robustness toward thermal fluctuations and canalize a broad range of morphological traits. Localization of harmful pathogens through tissue inflammation or through ingestion by macrophages	Monitoring/ controlling sub-system operating environments can reduce exposure to damaging perturbations. Fail-safe principles can dynamically encapsulate subsystems and prevent failures from propagating into expensive devices and system critical operations.
Mobility		
Mobility can enable agents to be relocated when hostile conditions develop	Predator avoidance, adaptive foraging, migration, and seed dispersal provide options for populations to seek out or track suitable habitats.	

Regulating the environment



Regulating the system



Different pathways, same requirements

Adaptive robustness require one or more of the following:

Changes in how much, when, and where resources are needed: This adaptation requires options to quickly ramp up a particular operation at a particular place and time.

Changes in task specifications: unexpected local conditions can require a function to be executed in a manner that deviates slightly from the norm. Maintaining diverse options for executing a task, each with unique vulnerabilities, can help to provide reliability under novel requirements. Option diversity is not random but reflects accumulated knowledge about expected disturbances, e.g. bet-hedging strategies reduce the likelihood of large systemic risks toward known uncertainties.

Functional novelty: New environments reveal opportunities to utilize existing components in novel ways: known to biologists as **exaptation**. Maintaining diversity of versatile options/ assets/agents can improve the likelihood of discovering and exploiting such opportunities.

Degeneracy

Definition: multi-functional agents that display similar functions in certain conditions, but different functions in others.

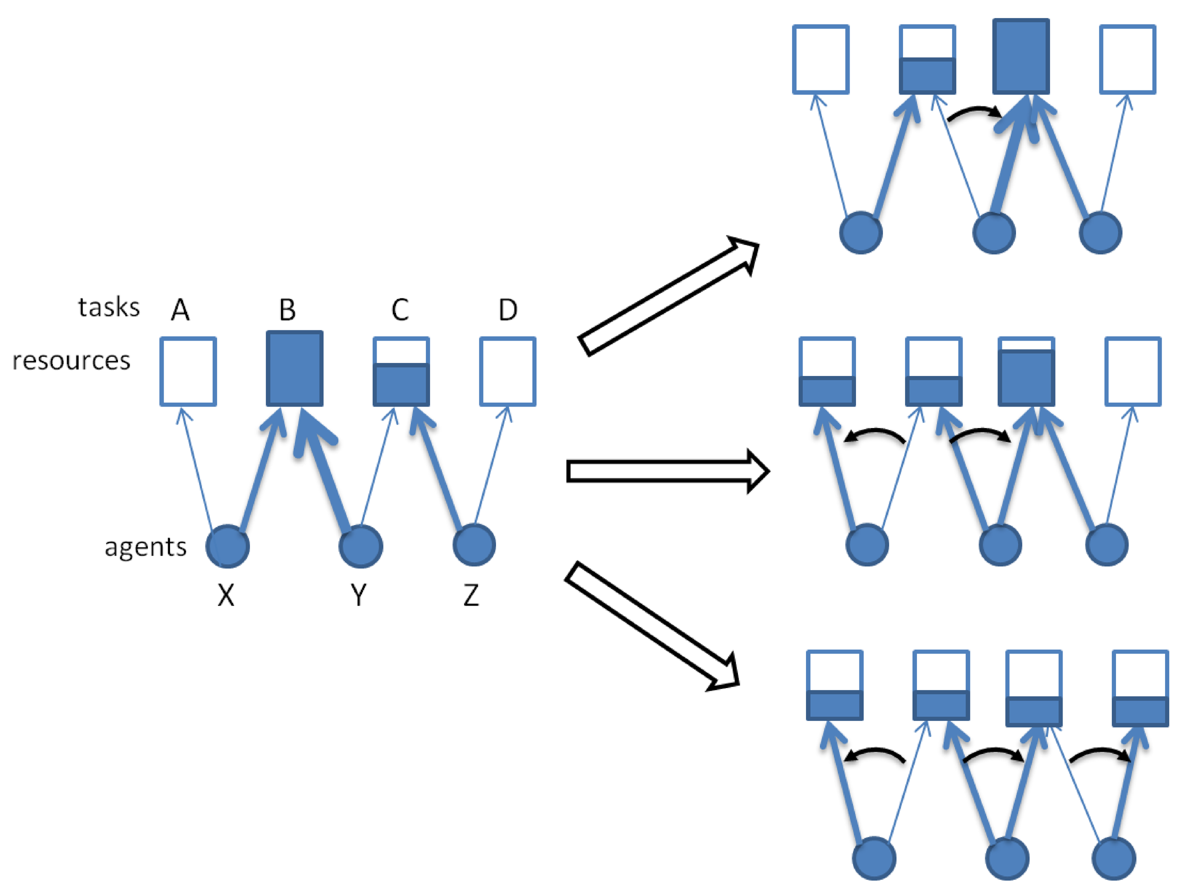
Degeneracy can contribute to many of the basic types of adaptation that support robust system responses. Importantly, the components underpinning both biological and social systems are versatile and semi-autonomous with behaviours that are strongly dependent on context and thus have the capacity for degeneracy to arise.

Systems where degeneracy is observed

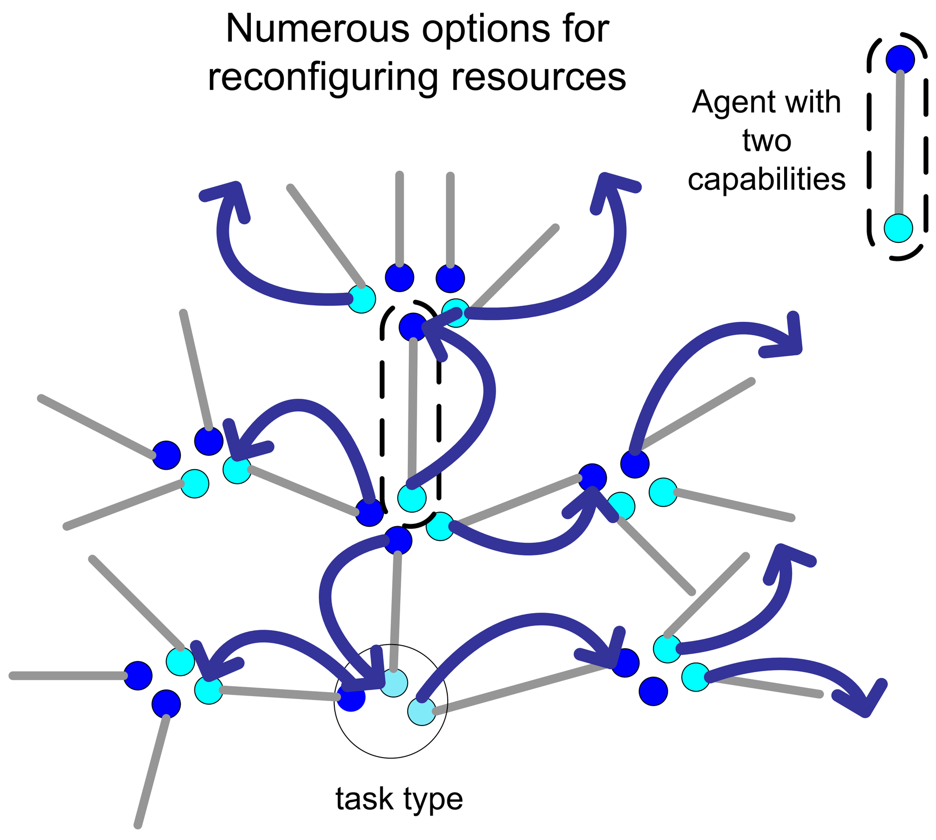
Agent	*System*	*Environment*	*Control*	*Agent Tasks*
Vehicle type	Transportation Fleet	Transportation Network	Centralized Command and Control	Transporting goods, pax
Force element	Defence Force Structure	Future Scenarios	Strategic Planning	Missions
Person	Organization	Marketplace	Management	Job Roles
Deme	Ecosystem	Physical Environment	Self-organized	Resource usage and creation
Gene Product	Interactome	Cell	Self-organized and evolved	Energetic and sterric interactions
Antigen	Immune System	Antibodies and host proteins	Immune learning	Recognizing foreign proteins

Types of adaptation supported by degeneracy

Flexibility in operational outputs: When multi-functional components are interoperable with other components in a subset of their functions (i.e. degenerate), fluctuating interoperability options can become synergistically linked as illustrated below. For instance, excess

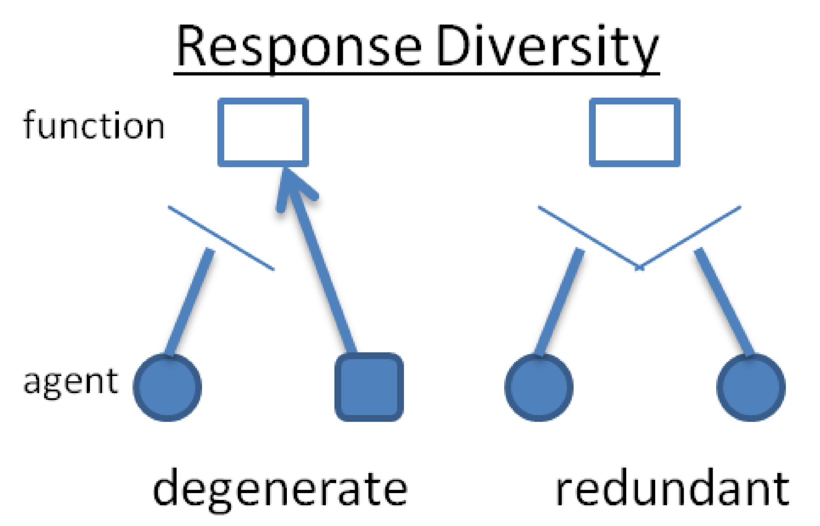


resources (agents) of multi-functional agent Y deconstrain task requirements for other partially interoperable agents (X & Z). As a result, the addition of agent Y resources will not only buffer variable demands for tasks B and C, it improves resource availability for tasks A and B (which are unrelated to agent Y) thus increasing the variety of demand fluctuations that the system can respond to and improving the tradeoff between robustness and efficiency.



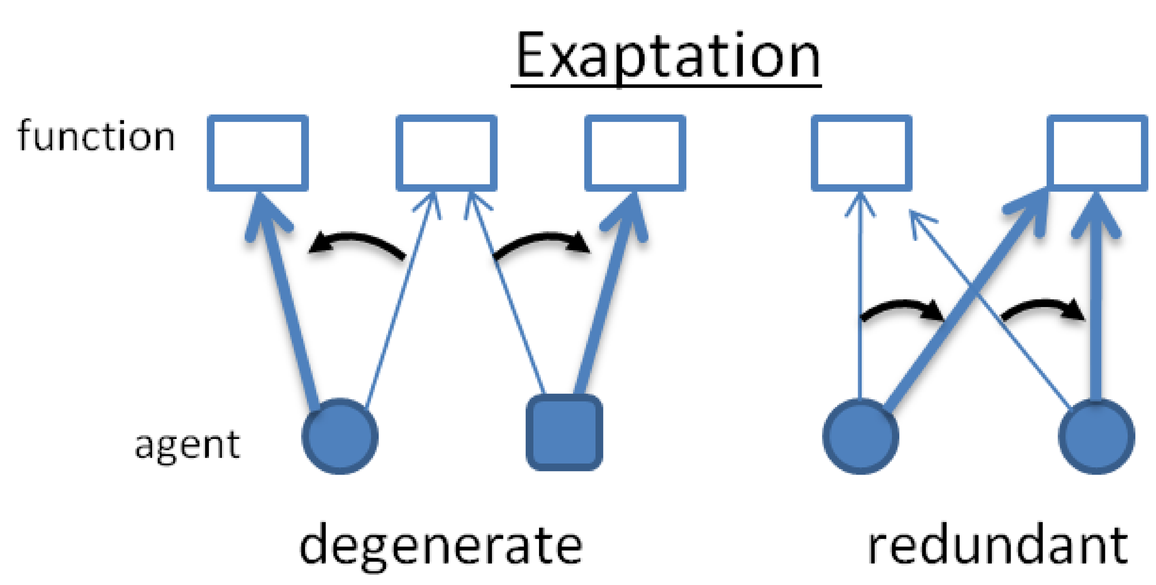
Networked Buffering: If interoperability is focused around a backbone of functions, the number of options for reorganizing resources in response to different task requirements can become very large , creating a new emergent form of distributed robustness.

Response Diversity: Agents that are degenerate will be functionally similar for certain tasks yet even for these tasks they display behavioural differences. Although these differences should not influence performance under conditions in which the agents are deemed interoperable, behavioural differences may correspond with differences in agent performance when tasks are executed under novel or rare conditions. Because of this potential



"response diversity", satisfying a particular task under unexpected novel conditions is more likely to be achievable by a repertoire of degenerate versus redundant agents. In a similar vein, degenerate components can harbour somewhat distinct vulnerabilities thus increasing the likelihood that at least one agent will not fail when confronted with a novel or rare challenge and thereby providing a basic form of bet-hedging.

Exaptation: Novel environments sometimes reveal opportunities for a component to be co-opted to perform new useful functions. With structural differences amongst degenerate components,



each component will harbour a different potential for co-option. A team of degenerate elements thus provides more opportunities for exploring innovative capabilities or responding to novel functional requirements.

References

Degeneracy Theory: Whitacre, J.M., Degeneracy: a link between evolvability, robustness and complexity in biological systems. Theoretical Biology and Medical Modelling, 2010. 7(6).

Networked Buffering: Whitacre, J.M. and A. Bender, Networked buffering: a basic mechanism for distributed robustness in complex adaptive systems. Theoretical Biology and Medical Modelling 2010. 7(20).

Exaptation: Whitacre, J.M. and S.P. Atamas, The Diversity Paradox: How Nature Resolves an Evolutionary Dilemma. Biology Direct, (in press).