Institutions and the performance of Coupled Infrastructure Systems

John M. Anderies* Marco Janssen†

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Abstract

Institutions, the rules of the game that shape repeated human interactions, clearly play a critical role in helping groups avoid the inefficient use of shared resources such as fisheries, freshwater, and the assimilative capacity of the environment. Institutions, however, are intimately intertwined with the human, social, and biophysical context within which they operate. Scholars typically are careful to take this context into account when studying institutions and Ostrom's Institutional Design Principles are a case in point. Scholars have tested whether Ostrom's Design Principles, which specify broad relationships between institutional arrangements and context, actually support successful governance of shared resources. This article, further contributes to this line of research by leveraging the notion of institutional design to outline a research trajectory focused on coupled infrastructure systems in which institutions are seen as one class of infrastructure among many that dynamically interact to produce outcomes.

Introduction

Many challenging problems facing modern societies involve social dilemmas related to natural resources and the environment. Readers of this journal will be intimately familiar with the notion of social dilemmas, indirectly referenced in the journal title through the word "commons". Many scholars have worked for decades to understand what characteristics of social organization enable groups to solve social dilemmas. Solutions to social dilemmas involve addressing one or both of two sub problems: 1) individuals face a choice in which the best outcome can only be achieved if many other decision makers make a choice that benefits the total payoff of the group and 2) there is no way to guarantee others will also make decisions that will benefit the group, so individuals face strong incentives to make a choice that is best for themselves and will have negative impacts on the group (Ostrom et al., 1994). After Hardin's 1968 work of almost 50 years ago set the tone, the dominant theoretical discourse around social dilemmas for the subsequent 20 years suggested that their solution required the intervention of an exogenous governance body that either a) directly restricts choices of actors thus removing challenge 2 of social dilemmas or b) establishes and enforces property rights removing challenge 1. Of course, these two solutions are just different sides of the same theoretical coin, differentiated by an arbitrary choice about the definition and assignment of "property rights".

Solutions based on one of these two options has dominated policy action spaces in developed countries for at least five decades. If anything, attempts at implementing these solutions have

*School of Human Evolution and Social Change and School of Sustainability Arizona State University. E-mail: m.anderies@asu.edu. Address: PO Box 875502, Tempe, AZ 85287-5502, USA.

†School of Sustainability Arizona State University. E-mail: Marco.Janssen@asu.edu. Address: PO Box 875502, Tempe, AZ 85287-5502, USA.

demonstrated that the devil is in the (practical implementation) details. Critiques often involve details of specific circumstances that either enabled or prevented the success of regulatory- or property-rights-based policy interventions (Acheson, 2006; Clark, 2006; Von Weizsaecker et al., 2005). E. Ostrom has referred to this mis-match between a small number of rather general policy prescriptions and the diversity of local contexts as panacea thinking, and called for academics and practitioners alike to move beyond it (Ostrom et al., 2007; Ostrom, 2010).

A large body of empirical research by commons scholars provides us with many case studies in which communities have been able to solve social dilemmas in a variety of common pool resource (CPR) contexts using a wide range of alternative institutional arrangements. Although these examples provide some direction for how to move beyond policy panaceas, they also challenge us to make sense out of the variation in the data. On the one hand, we have claimed that simple panacea solutions won't work but on the other, does each social-ecological context require its own fine-tuned set institutional arrangements of the kind that result from relatively long-term, dynamic coevolutionary processes? Can we identify empirical patterns across highly variable, detailed case studies that are useful for the analysis of modern policy problems? A key challenge scholars face in addressing these questions is to identify structure within the entire range of endogenously generated and enforced institutional arrangements capable of governing CPRs. Or goal with this paper is to explore how we might leverage ideas for institutional analysis and systems science to address this challenge.

Refining the Challenge

Fortunately, the research community has already come a considerable distance in identifying and characterizing structure in the wide variety of institutional arrangements observed in practice. With "institutional arrangements" we refer to clusters of rules, assembled from any number of individual rules based on building blocks from seven rule classes (Ostrom et al., 1994) that specify what actions are allowed or required, what information is accessible, and how costs and benefits are attached to actions and outcomes. A moment's reflection will reveal the challenge in identifying structure in such clusters of rules: the diversity of possible viable institutional arrangements for any given CPR dilemma is enormous. Ostrom and colleagues have made a huge effort through her comparison of hundreds of case studies from irrigation, forestry, fisheries, and ground water systems to give some meaningful structure to the enormous variation in institutional arrangements possible in theory and observed in practice. Ostrom developed 8 *design principles*, familiar to readers of this journal, that describe broad features (i.e. structure) of rule clusters associated with successful CPR governance regimes and, thus, form a basis for assembling rule clusters (i.e. *designing* institutions) capable of helping solve social dilemmas in CPR contexts. Ostrom later regretted to use the term design principles since they were hypotheses emerging from case studies rather than blue prints for how to govern the commons (Ostrom et al., 2007).

Ultimately, building a stronger empirical and theoretical basis for the Design Principles will be required to demonstrate their value. This requires the development and use of a systematic, robustly replicable methodology for case study analysis. It turns out that this is a difficult task for both practical and theoretical reasons. The foremost practical constraint is the magnitude of the task of systematically extracting data from many case studies of social-ecological systems. Ideally, the same data would be collected with the same protocol in many study sites around the world for many years. Such an endeavor would be very costly would unlikely attract funding (but see Wollenberg et al., 2007). In reality, most of the analysis of case studies depends on the extraction of data from secondary sources generated by scholars who collected data using different protocols to address different research questions. This makes it difficult to reconcile and compare data drawn from different secondary sources.

Second is the challenge of developing a robustly replicable methodology to "code" the cases. As Ratajczyk et al. (2016, this issue) discuss, the coding of qualitative data requires multiple coders systematically applying a coding protocol and discussing their results to resolve different interpretations of the qualitative information. Given these challenges, it is not surprising that beyond Ostrom's large-N comparative analysis conducted to develop the Design Principles, there have been very few studies that systematically test the design principles 'out of sample'. There are several interesting examples in which scholars search for the occurrence of particular instantiations of the Design Principles in particular contexts such as irrigation in Nepal (Ostrom and Benjamin, 1993), agro-pastoralism in Tanzania (Quinn et al., 2007), and forestry cooperatives in Peru (Morrow and Hull, 1996). The conclusions that can be drawn from such studies are typically limited to demonstrating that some subset of the design principles is present and that one or two of those present seemed to have contributed to better governance *in a particular situation* under investigation by the authors.

Finally, supposing that the problems of reconciling data from different secondary sources and applying a coding protocol in a robustly replicable way were solved, we are left with the challenge of analyzing the data. Even if we limit the coding to presence or absence of the 8 design principles, this allows for 256 possible institutional configurations. Further, we must account for the fact that each of these 256 possible configurations may produce different outcomes depending on the context in which they operate. There is a useful analogy between how genes and gene regulatory networks guide organism development and how the design principles and networks of social and technological infrastructure impact social forms which we draw out further below.

The work of Baggio et al. (2016) and Barnett et al. (2016) in this special issue is a first step in attempting to understand how institutional configurations may produce different outcomes depending on the context in which they operate. As we might expect, just as we now know with genes, the Design Principles do not operate individually. Rather, they co-occur in particular patterns, and those configurations depend on the social and biophysical context. It is important to note that Ostrom's IAD framework defined the context as "external variables" that are held fixed for analysis. This is appropriate for an analysis of short term performance of systems. However, with the increasing focus on understanding the robustness and resilience of interactions between social and biophysical systems, contextual variables should be viewed as part of a complex adaptive system in which institutional arrangements, social, and biophysical components co-determine one another and coevolve over time. If our interest is in the design of systems that are robust and resilient, we need to take into account the structure and dynamics of all the attributes of the system in which institutional arrangements are endogenously determined. We can't view institutional arrangements as causal factors in isolation.

The collaborative project reported in this special issue and our own work on irrigation systems (Anderies and Janssen, 2013; Janssen and Anderies, 2013) provides some insights for what a framework to study the structure and dynamics of systems might look like. The basic premise is that we view the system of interest as a set of different types of infrastructures that dynamically interact. Institutions are then viewed as one particular class of infrastructure. The contribution of this paper to the special feature is thus to complement the other papers that have taken steps to grapple with the data and coding problems inherent to studying the commons (Ratajczyk et al. 2016) and uncover richer structure in institutional arrangements (Baggio et al. 2016) by outlining a framework to enable us to better understand the dynamic interplay between institutional structure and context. In the remainder of the paper, we flesh out the rationale for and details of the proposed framework.

On the Study of Coupled Infrastructure Systems

While the IAD framework has been in use for over 30 years (e.g. at least since Kiser and Ostrom (1982)), and is probably the most commonly-used framework for thinking about institutions in social-ecological systems, there remains significant variation in how the IAD Framework is adopted in practice. The need for continued clarification and sharpening of the framework is evidenced in Ostrom's own writing. Specifically, in 2011 she wrote a review article as part of a special feature on applications of the IAD framework with the purpose of clarifying the intellectual basis of the IAD and "discuss how and why the framework itself has changed over time" (Ostrom, 2011, p. 7). The papers presented in this special feature can be seen as clarifying the way different elements that constitute the action situation, a core component of the IAD, intermingle to produce outcomes in social-ecological systems.

In the same way that the IAD framework has evolved over time based on feedback from its users, we suggest further extensions of the more recent outgrowths of the IAD such as the Social-Ecological System (Ostrom, 2009) and Robustness frameworks (Anderies et al., 2004) as detailed below. We suggest this extension based on our long-term collaboration with Ostrom on developing methods for studying the evolution of action situations over time which she saw as a key future challenge (Ostrom, 2011). The purpose of the extension is to make collective action problems related to the creation and maintenance of infrastructure and the distributions of the outputs it generates a central focus of analysis. In Anderies et al. (2004) we used infrastructure as a common aspect of the social ecological system building on Ostrom's research on small-scale irrigation systems.

Our work on irrigation systems and other types of social-ecological systems (such as reported in this special issue) has led us to recognize that technology, environment, rules, norms, beliefs, and social bonds are intimately intertwined. Instead of the term "Social-Ecological System", we now use the term "Coupled Infrastructure System". The term social-ecological systems implies there are two distinct domains, the social and the ecological that operate by their own logic (although they can intimately interact). The term coupled infrastructure system, on the other hand, suggests that there is only infrastructure, defined as structures of any kind, e.g. genomes, legal systems, roads and bridges, knowledge and value systems, buildings, and ecosystems that provide affordances when combined with other classes of infrastructure to produce mass and information flows we value. With "affordance" we mean the potential outcomes that are accessible to actors in an action situation to an individual, independent of the individual's ability to perceive this possibility. For example, a tree does not generate wood that can be used as building material. It does, however, provide an *affordance* for producing building material to a skilled person with an axe. Computer hardware is useless without software. The hardware provides only an affordance for computational capacity. Likewise, the capacity of roads to provide transportation opportunities is limited without institutional arrangements for the use of the road. The work in this special issue focuses on how natural (e.g. ecosystems), hard human-made (technology), and soft human-made (institutions) infrastructures interact to produce outcomes in social dilemmas related to public good provision and resource governance. By describing our systems of interest as combinations of different types of infrastructure in which institutional arrangements are one type, we emphasize the dependencies of those different types of infrastructures to generate desired outcomes from the system.

Examples of the 5 main types of infrastructure that constitute coupled infrastructure systems are: (1) hard infrastructure which is human-made structures such as roads, irrigation systems, and nuclear power stations. (2) soft infrastructure which are human-made "instructions" for using other types of infrastructure. Institutions are examples of soft infrastructure. (3) natural infrastructure which is hard infrastructure that is not human-made but still is critical for society, such as wetlands for absorbing and filtrating water, (4) human infrastructure which refers to knowledge (often referred to as "knowledge capital" in economics), and (5) social infrastructure which refers to the relationships we have with others.

All these types of infrastructure have common characteristics that impact collective action problems in important ways. The creation of shared infrastructure typically requires investment from a large number of people. Once infrastructure has been created, it requires maintenance to maintain its performance at the levels for which it was initially designed. We have to invest resources in the form of time and energy to maintain roads, enforce rules, sustain wetlands, keep up our knowledge and maintain relationships. Finally, the outcomes generated from the interactions of infrastructures often have distributional effects. How are the benefits allocated, and access arranged? Inequality and power differences are important characteristics of coupled infrastructure systems that can impact their performance.

Another aspect of a focus on infrastructure is that it highlights the importance of path dependency and in systems. Investments made to create new infrastructure can have lasting effects. Transitioning from a fossil fuel based energy system to one based on distributed renewable resources is hindered by the sunk costs associated with the infrastructure that supports the existing energy system. Changing human behavior can be hindered by existing habits, entrenched social norms, and social commitments. A common saying is that science progresses with every funeral, referring to the reluctance of the existing scientific establishment to adopt new scientific paradigms.

Looking at systems on a longer time scale enables us to look at the interactions of different types of infrastructure and generate understanding about which configurations of infrastructure enhance resilience or enable transformations. If we look at the rapid change in communication technology since the 1990s, we see that the combination of hard infrastructure (devices, internet, etc), soft infrastructure (world wide web, software applications), and social infrastructure (social networks in person and online) have led to a rapid co-evolution of the information transmission and exchange infrastructure that defines our age.

This co-evolutionary perspective addresses some of the directions by which Ostrom (2011) suggested institutional analysis can advance. She suggests we need (1) a better understanding of the factors that structure action situations, and (2) a better understanding how action situations evolve over time through changing perceptions induced by recursive interactions. With a coupled infrastructure systems perspective we have a more dynamic view that makes more explicit the interactions between outcomes and the "external variables". In fact, the IAD framework has an implicit temporal sequence. First, biophysical conditions, attributes of the community, and rules-in-use combine to form the structure of the action situation. Next, individuals interact within the action situation and produce outcomes. This is followed by an evaluation of the outcomes. Finally, these outcomes may induce actors to change the rules-in-use (at the collective choice level), their perceptions (attributes of the community, or technology (biophysical conditions) through feedback. This feedback is explicitly depicted in the IAD framework (Ostrom, 2005) and suggests that the evolutionary dynamics of action situations can be conceptualized as a recursive relation on the system states related to biophysical context (state of the environment, state of technology), attributes of the community (perceptions, knowledge), and institutions (rules of the game) with reasonably identifiable time scales. The notion of governance as the dynamic evolution of action situations is a powerful analytical frame, but the research that underlies the work presented in this special feature suggests we must take care for at least two reasons:

- The notion of governance must more strongly emphasize the importance of features other than social interactions in producing outcomes. The notion of action situations can tend to focus the analyst's attention on social interactions. In some cases, outcomes may depend less on social interactions than on other processes and, as a result, the details of social interactions in a particular case may not help us understand "successful governance" in that case. This is especially true for practical aspects of effective monitoring and sanctioning processes that typically receive less attention in the literature than institutional arrangements (understood as rules and norms), trust, and communication.

- It is likely the dynamic evolution of action situations involves interactions at a very large number of time scales that are difficult to identify, giving rise to subtle interactions that are difficult to disentangle. Such a view acknowledges the difficulty, for example, of understanding how formal and informal institutions interact, how institutions interact with perceptions, and how all these interact with technology.

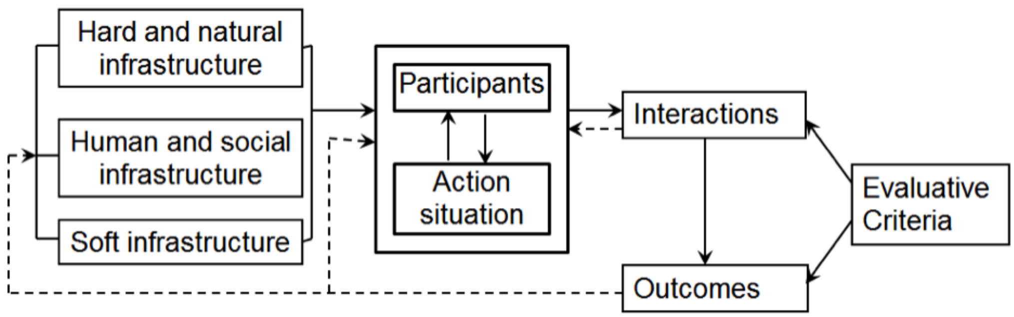

Figure 1: *The Institutional Analysis and Development framework from the perspective of coupled infrastructure systems.*

We now present the IAD framework from a CIS perspective by using the different types of infrastructure defined above to characterize the broader context. We replace the biophysical conditions with hard and natural infrastructure, reflecting the fact that the biophysical conditions include both human-made and natural hard infrastructure. We replace the attributes of the community with human and social infrastructure to capture the knowledge and social capital within the community. Finally, the rules-in-use is replaced by soft human-made infrastructure.

If we focus on the action situation, we can also define a more dynamic perspective. We illustrate this with some examples using Ostrom's notion of the internal structure of an action situation that emphasizes 'institutions as rules' shown in Figure 2 (in black). Here, elements from the seven classes of rules mentioned above determine what positions can be assumed by actors in the action situation such as *chair* or *director* (through **position rules**), which actors may assume those postions, e.g. must be a member of the village, (through **boundary rules**), and what actions actors in positions can take (through **choice rules**). Choices are linked to outcomes via how much information actors have (through **information rules**), and how much control individual actors have (through **aggregation rules**). Potential outcomes are limited by **scope rules**. Finally, actors make decisions in action situations by assigning costs and benefits to outcomes which are conditioned by **payoff rules**. Thus, by restricting some actions and enabling others, institutions structure the action situation and move the system of recurring action situations toward desirable outcomes. In this view, institutions are protocols that help *animate* coupled infrastructure systems given biophysical constraints.

While this view of *institutions as rules* is powerful, the two points above suggests an alternative view that may better characterize some situations. Specifically, the second point suggests that in some situations we may reverse causality and replace "assigned to" with "emerge from" as shown in red. In this case, actors are constantly generating new self-images and mental models as they occupy positions in networks of social relations in essence defining new actors and new possible actions. Likewise, the arrows between the action situation and rules regarding information, control, outcomes, and costs and benefits are reversed (again shown in red). In this view, institutions are not rules that guide action and animate social interactions but, rather, are reflections of common knowledge regarding self-sustaining features of social interactions (Aoki, 2007, 2001). Rules are then codified public representations of this common knowledge. Aoki (2007) suggests that we might label the black arrow and text version of Figure 2 as the "exogenous" and the red version the "endogenous" view of institutions. In the endogenous view, institutions are emergent features of the dynamic interaction between the various classes of infrastructure that constitute the action situation generated by a large number of microsituational variables. Lobster fisheries illustrate

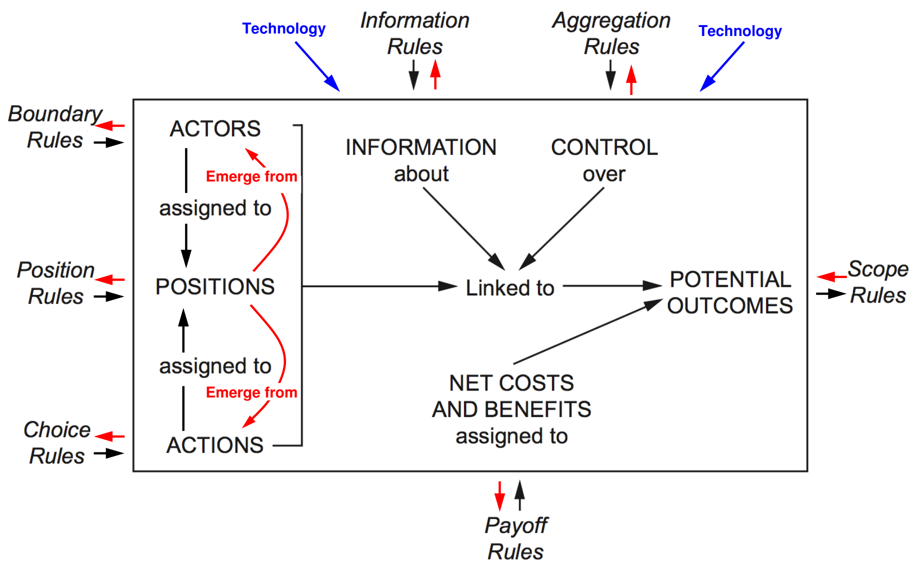

Figure 2: *Ostrom's schematic for the internal structure of the action situation emphasizing the role of rule clusters in structuring action situations. Adapted from Ostrom (2011, Figure 3).*

the importance of the first point. Lobster traps have buoys that convey information about who is fishing where and the way lobster traps are set and recovered strongly conditions catch. Lobstering technology makes the costs of monitoring (buoys are easy to see) and sanctioning (traps are easy to cut/destroy) relatively low. Thus, successful governance of lobster fisheries may have more to do with the specifics of technology than with institutional arrangements. Put simply, a given coupled infrastructure system may simply have gotten lucky, by its very constitution, and thus was able to "solve" a perceived (by an outside observer) social dilemma that actually doesn't exist. For example, the Nyamaropa forests as discussed in Barnet et al. (2016) was defined to be successful, but this was mainly caused by an abundance of forest resources.

Research challenges and opportunities for CISs

Now that we have defined a new perspective based on an extension of the IAD Framework to study the governance of shared resources, we will close by introducing some research opportunities that emerge from taking a coupled infrastructure system perspective. As discussed in Ratajczyk et al. (2016) a critical challenge in coding case studies is a consistent mutual understanding of the qualitative information available. Although we discuss the results in this special issue from the perspective of CPR systems, we began using the coupled infrastructure systems view during the project which provided a helpful consistent terminology for our team. We will advance the coding protocols in later versions that will be more in line with the coupled infrastructure system perspective.

Secondly, a challenge that the coupled infrastructure perspective helps address is the dynamic, multi-scale nature of many resource systems which are difficult to code. An infrastructure perspective may help by providing consistent terminology that can be easily understood used across multiple disciplines such as economics, engineering, and political science. An example might be to code the rate of decline of the performance of particular classes of infrastructure in a given system; a critical feature of many systems that a focus on rules and social interacts would miss.

Thirdly, the coupled infrastructure system perspective enables researchers to broaden the scope of case studies to include, for example, challenges in urban systems. In fact, one of the main challenges in the coming years will be to maintain the performance of hard infrastructure such as energy and fresh water production and distribution infrastructure as well as road and rail systems. Hurricane Katrina and Sandy had major impacts in New Orleans and New York and demonstrated the vulnerability of hard infrastructure to natural shocks. However, this is not just an engineering problem (Karvonen, 2011; LePatner, 2010). We argue that a broader perspective is needed to study these types of problems, and that looking at the interactions among different types infrastructure is a step in the right direction. For example, Mexico City is built on a lake, has flooding problems, but at the same time lacks the capacity for reliable distribution of clean fresh water to most neighborhoods. Many problems associated with different infrastructure systems converge in this case including those affecting an under provision of maintenance of infrastructure, others that result in a low level of waste water treatment capacity within Mexico City, and still others related to collection of garbage which, when not done properly leaves garbage in the street which can end up clogging the water flow systems.

We hope that our reflection on some of the lessons learned from the research reported in this special issue and the introduction of the notion of coupled infrastructure systems will stimulate a discussion in the commons research community about how we can work together to improve the comparative analysis of case studies of shared resources beyond the scope Ostrom originally addressed. We hope this fosters the development of new theory and new communities of practice.

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