An Agent-Based Dynamic Model of Politics, Fertility and Economic Development

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Abstract. In the political economy of development, government policy choices at a single point in time can dramatically affect a country's development path by impacting fertility, economic and political decisions across generations. Combining both system dynamics and agent-based modeling approaches in a complex adaptive system, I formalize a simulation framework of the Politics of Fertility and Economic Development (POFED) to understand the relationship between politics, economic, and demography change at both macro and micro levels. First, I validate Abdollahian et al. [1] system dynamics model with the latest data and updated political capacity measurement. Second, I fuse these endogenous attributes with non-cooperative game theory in an agent-based framework to simulate the interactive political economic dynamics of individual intra-societal transactions. Third, I connect macro and micro level with policy levers of political capacity and political instability, by merging system dynamics and agent-based components. I explore the model's behavioral dynamics via simulation methods to identify paths towards economic development and political stability. This work explains micro level human agency can act, react and interact, thus driving macro level dynamics, as well as how macro structures provide political, social and economic environments that constrain or incentivize micro level human behavior.
Keywords: economic development, politics, demographic change, agent-based model system dynamics, game theory; complex adaptive systems

1 Introduction

This study investigates countries' growth paths under different economic, political, social, and demographic conditions. Growth and development has been an important issue in the field of political economy. Among existing studies, two faces of development attract considerable attention: one is a poverty trap with persistent economic stagnation; the other is industrialization and rising incomes. It is argued that political development, measured as political stability and political capacity, is sometimes identified as a cause of economic growth and fertility decision, but sometimes as a consequence of it [8][14]. On the other hand, economic development is sometimes modeled to have an impact on human capital and political development, but sometimes as a result of fertility decision and political institution [8][9][13][14].

The rich literature in this field mostly focuses at macro level. Countries are used as unit of analysis or specific cases. Empirical research uses macro structural, society level variables, like GDP, GDP growth, fertility rate, and literacy rate among others to test different theories. Each one of these indicators is the sum of millions of human choices, samples at arbitrary annual frequencies from an imperfect data and population distribution. However, the micro level is very poorly studied, and the linkage between macro constraints and micro level choices remains undiscovered for POFED. Therefore, it makes sense to investigate income level, fertility decision, and education at micro level of human agency, to better understand how individuals make critical decisions and how they behave. In addition, it will also be critical to understand how macro environment impacts individual decision, and the feedback of individual behavior that subsequently shapes and shifts macro societal trends and conditions.

2 POFED Background

For many decades, there have been contradictory findings in studies of the political economy of growth, exploring the factors that lead to either steady growth or a poverty trap, including political factors, demographic factors, social and economic factors. Scholars argue demographic change has significant impact on economic growth, with fertility rate and human capital as the two most important attributes [13][14]. Besides demographic patterns, political factors are also playing a critical role in a country's growth path. For example, Feng et al. [12] argues political freedom is capable of producing sustainable long-run economic growth once an identified threshold is exceeded. Even a one-time change in the political environment affects economic factors over many generations, and the political condition can be captured via a few critical variables like political stability and political capacity [13][14].

Feng et al [14] presents a formal model that characterizes the two faces of development—persistent poverty, and industrialization and rising incomes, and establishes that the interaction between politics and economics determines which path a nation travels. In one of the latest POFED literature, Abdollahian et al. [1] emphasizes the dynamic interrelationships between income *y*, fertility *b*, political effectiveness *x*, and social stability *s*. They specify the model as:

$$b_t=\lambda_1 \bullet \ y_t{}^{\alpha 1};$$
$$y_{t+1}= \lambda_2 \bullet \ y_t{}^{\alpha 2} \ \bullet \ h_t{}^{\beta 2} \ \bullet \ s_t{}^{\gamma 2} \ \bullet \ x_t{}^{\delta 2};$$
$$s_{t+1}=\lambda_3 \ \bullet \ s_{t-1}{}^{\alpha 3} \ \bullet \ x_t{}^{\beta 3} \ \bullet \ (\frac{x_t}{x_{t-1}})^{\gamma 3};$$
$$h_{t+1}=\lambda_4 \ \bullet \ b_t{}^{\alpha 4} \ \bullet \ h_t{}^{\beta 3};$$
$$x_t=\lambda_5 \ \bullet \ (\frac{y_t}{b_t})^{\alpha 5} \ \bullet \ s_t{}^{\beta 5}.$$

These equations show that fertility rates b depend on income y; and that income depends on past income and political conditions, x. The fourth equation h shows the generational feedback on the creation of human capital, while in the third equation political instability, s, has a temporal feedback and depends on political capacity. Similarly, political capacity, x, depends on per capita income y, fertility rate b, and instability s. This system of equations describes how the five main components work at society level, which can be empirically tested via two systems of equations, one at aggregated individual level focusing on human capital, fertility, and income, and the other at society level focusing on instability and political capacity.

3 Complex Adaptive Systems

Rooted in international political economy, POFED is a qualitative, trans-disciplinary approach to understanding growth and development through the lens of interdependent economic, demographic, social and political forces at multiple scales, from individuals to institutions and society as a whole. Here I extend previous work by Abdollahian et al.'s [1] quantitative systems dynamic representation of POFED at the societal level towards integrated macro–micro scales in an agent-based framework. As macroscopic structures emerging from microscopic events lead to entrainment and modification of both, co-evolutionary processes are created over time. Quek et al. [23] also design an interactive macro–micro agent-based framework, which they call a spatial Evolutionary Multi-Agent Social Network (EMAS), on the dynamics of civil violence. I posit a new approach where agency matters: individual game interactions, strategy decisions and outcome histories determine an individual's experience. These decisions are constrained or incentivized by the changing macroeconomic, demographic pattern, social and political environment via POFED theory, conditioned on individual attributes at any particular time. Emergent behavior results from individuals' current feasible choice set, conditioned upon macro environment. Conversely, progress on economic development, the level of internal instability, and population structure emerge from individuals' behavior interactions.

In order to create a robust techno-social simulation [27] platform, first I instantiate a system of coupled nonlinear difference equations that capture the core logic of POFED macro-social theory. Following Abdollahian et al [2-4] approach, I then empirically validated with updated real data with fertility, income, and human capital from World Bank [29], instability and political capacity from Kugler and Tammen [18].

$$\begin{cases} fertility_t = \beta_{10} + \beta_{11} fertility + \beta_{12} income_{t-1} + \varepsilon_1 ; \\ income_t = \beta_{20} + \beta_{21} income_{t-1} + \beta_{22} human\ capital_{t-1} + \beta_{23} instability_{t-1} + \beta_{24} political\ capacity_{t-1} + \varepsilon_2 ; \\ human\ capital_t = \beta_{30} + \beta_{31} human\ capital + \beta_{32} fertility_{t-1} + \varepsilon_3 ; \end{cases}$$

$$\begin{cases} instability_t = \beta_{40} + \beta_{41} instability_{t-1} + \beta_{42} political\ capacity_{t-1} + \beta_{43} \dfrac{political\ capacity_t}{political\ capacity_{t-1}} + \varepsilon_4 ; \\ political\ capacity_t = \beta_{50} + \beta_{51} political\ capacity_{t-1} + \beta_{52} \dfrac{income_{t-1}}{fertility_{t-1}} + \beta_{53} instability_{t-1} + \varepsilon_5 . \end{cases}$$

Similar to Quek et al. [25], second I then fuse POFED endogenous systems to agent attribute changes with a generalizable, non-cooperative Prisoner's Dilemma game following Axelrod [5-7], Nowak and Sigmund [21][22] to simulate intra-societal, spatial economic transactions. Understanding the interactive political effects of macro-socio dynamics and individual agency in intra-societal transactions are key elements of a complex adaptive systems approach. Finally, I explore the model's behavioral dynamics via simulation methods to identify paths and pitfalls towards economic, social, demographic and political development as well as societal cooperation across different stages of development. I find strong interactions, where strategies are interdependent, and local social co-evolution [17], help determine global-macro development outcomes in a particular society.

4 POFED in an Agent-Based Framework

I propose an agent-based model in a complex adaptive system framework that captures both macro level changes and micro level behavior by incorporating system dynamics component and game theory component. Following the work by Abdollahian et al [2-4], my agent-based model has both the interactive effects and feedbacks between individual human agency as well as the macro constraints and opportunities that change over time for any given society. Individual decisions are affected by other individuals, social context, and system states. These elements have first and second order effects, given any particular system state or individual attributes.

Such an approach attempts to increase both theoretical and empirical verisimilitude for some key elements of complexity processes, emergence, connectivity, interdependence and feedback found throughout several disciplines across all scales of modernization and human development. Figure 1 depicts the high level process and multi-module architecture. There are three modules in the agent-based model: micro agent process, macro society process, and heterogenous evolutionary game process.

The design of the micro agent process module incorporates system dynamics, which allows each individual agent to behave as a system. Traditional approaches in political science are static and cannot capture the dynamic feedback loops that reflect real-worlds complexity, assuming time plays no role. System dynamics models can be used when behavior of the system changes over time and is statistically significant. I maintain individual agent variable relationships and changes following the latest POFED literature [1]. These endogenously derived individual agent variables impact how economic transaction games occur, based on society variables either increasing or decreasing individual wealth and ultimately societal productivity [7]. Thus I create the population by adjusting the mean and standard deviation of fertility, income, and human capital at the society level. Each individual agent carries all three variables that are randomized from the society's distribution. At the beginning of this process, agents are allowed to give birth to new agents based on their fertility variable. To capture this individual agent endogenous processes, I use empirically validated parameter values from Three Stage Least Square estimation as a good first approximation. This method has been widely used by many scholars in recent [2-4] to simulate the dynamic process at individual level. In this module, feedback is used to model individual and social phenomena. The value of system dynamic component is tied to the extent that constructs and parameters represent actual observed project states. As discussed in Madachy, System dynamics models help facilitate human understanding and communication of the process, and are more accurate to model time-based relationships between factors and simulate a system continuously over time.

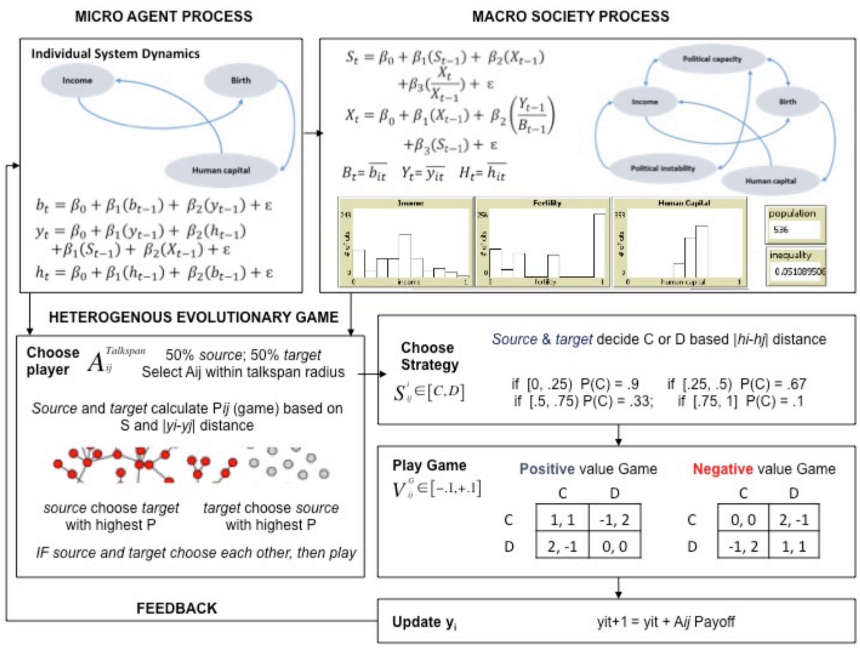

Fig. 1. POFED Agent-Based Model Architecture

Similar to micro agent process, I also use system dynamics technique in this macro society process. Instead of taking each individual agent as a system, this module takes the entire society as the system, with political instability, political capacity, economic condition, human capital, and fertility rate as main attributes. This module is critical as it connects micro individual level and macro society level. Society economic condition is aggregated from individual wealth by taking the mean. Human capital is aggregated from individual level of education, and fertility rate is also aggregated from individual level in the same way. The feedback loop is completed in the way that initial individual variables are randomized from the society distribution, get updated in micro agent process and evolutionary game process, then get aggregated at society level and interact with other society variables, while society variables also impact the evolutionary game process. I also use empirically validated parameter values from Three Stage Least Square estimation in the simulation. The updated instability is brought into the evolutionary game process to affect the probability that agents interact with each other. This feedback loop is extremely helpful when I focus on how individual behavior changes macro environment, and how environment in turn impacts individual behavior.

Evolutionary game theory provides insights into understanding individual, repeated societal transactions in heterogeneous populations [15][25]. Social co-evolutionary systems allow each individual to either influence or be influenced by all other individuals as well as macro society [25][30][26], perhaps eventually becoming coupled and quasi-path interdependent. In my POFED model, I do not have well mixed populations, but explicit spatial contact networks given population density, technology diffusion and agent attributes. Thus I explicitly recognize that the differential impact of heterogeneous, spatial structures matters. This captures various individual preferences and their socioeconomic variables.

Therefore, after micro agent process and macro society process, I choose to focus on Prisoner's Dilemma in the macro political stability environment. In this model, variable talkspan defines spatial proximity interactions, ranging from 1 to 20, defining the grid size radius for the local neighborhood. At talkspan of 1, citizens only interact and calculate probability of playing the transaction game with direct neighbors, while at 20, citizens can potentially interact up to 1200 neighbors. To model communications and technology diffusion for frequency and social tie formation [19], I have agent i evaluate the likelihood of conducting a simple socio-economic transaction with agent j based on similarity of income level $|y_i - y_j|$, stability of the environment, and physical distance talkspan, This also reflects recent work on the importance of both dynamic strategies and updating rules based on agent attributes affecting co-evolution [17][20][3][4].

At every time period, I randomly choose 50% of the agents to be sources who can choose a partner; and the remaining targets to be chosen by other agents based on symmetric preference rankings but asymmetric proximity distributions. Social Judgment Theory [10][16] describes how the positions of two agents can be conceived along a Downsian ideological continuum [12] and distance between these positions affects the likelihood of one accepting the other's position. Source agents evaluate the average y between themselves and all target agents within a given neighborhood radius. Smaller income difference increases the probability that A^{ij} will enter into a socio economic transaction and play a non-cooperative game. This is the first probability that will impact the choice of target.

The second probability that goes into the calculation come from society attribute, instability, measured as the proportion of a country's physical capital destroyed in antigovernment violence [8][9]. As discussed in a lot of literature [13][14][1], political instability impacts individual decision and capital accumulation. In an unstable environment, people have less incentive to conduct economic activities, so the probability of playing a socio-economic transaction game is low in such condition. When political instability is low, people are more likely to interact with each other so the probability is high. The multiplication of the two probabilities determines the probability that the source agent plays the transaction game with the target agent.

After each source agent calculates its probability of playing a game with all possible target agents, it chooses the target with the highest probability to be its partner. The target agents also repeat the same process symmetrically, then chooses the A^{ij} pairing highest probability derived from its preference-proximity function as its partner.

After they decide to play, agents choose strategies based on $|h_i$-$h_j|$. Siero and Doosje [24] among others show that messages close to a receiver's position has little effect, while those far from a receiver's position is likely to be rejected. So when the difference of human capital is small, there is a high probability of playing cooperate while long distance results in high probability of playing defect. The relative payoff for each agent is calculated based on simple PD, non-cooperative game theory [25][21][11] where T>R>P>S, with T= 2, R=1, P = 0 and S= -1. When both agents cooperate, they both gain TT; when one plays cooperate but the other plays defect, the cooperating one loses while the defecting one gains ST; when both play defect they don't gain anything from the transaction PP. The updated y_{t+1}^{i}= + (Relative A^{ij} Payoff)t, which goes back to agent *i* endogenous POFED processing for *t*+*n* calculations.

In the next step, I setup non-cooperative A^{ij} games whose outcomes condition agent y^i values for the next iteration. Following Nowak and Sigmund, I first randomly assign the value of any transaction [-0.1, 0.1] to model different potential deal sizes, costs, benefits, or synergies of any social interactions. Following Abdollahian et al. [2-4], I specifically model socio-economic transaction games as producing either positive or negative values as I want to capture behavioral outcomes from games with both upside gains or downside losses. Subsequently, A^{ij} games' V^{ij} outcomes condition agent y_{t+1}^{i} values, modeling realized costs or benefits from any particular interaction.

The updated y_{t+1}^{i} = y_t^i+ A^{ij} game payoff for each agent then gets added to the individual's variables for the next iteration. I then repeat individual endogenous processing, aggregated up to society as a whole and repeat the game processes for *t*+*n* iterations, where *n* is the last iterate.

In this module, A^i strategies are adaptive, which affect A^{ij} pairs locally within an approximate radius as first order effects. Other agents, within the society but outside the talkspan radius, are impacted through cascading higher orders. Following Abdollahian et al. [2], I explicitly model interactions [17] to capture co-evolutionary behavior in a simple, yet elegant manner. Although easily done, I specifically do not model mathematically complex, individual agent memory or learning from V^{ij} outcomes as many others do [5][25][3]. However, memory and history still matters. The sum of all prior individual system dynamics behavior and evolutionary through iterations, does contribute to each individual and societal current states.

As an initial effort at a scale integrated framework, the design of three modules frees me to focus on the coupling of structure and agency first, before enriching subcomponent process detail. Thus agents simultaneously co-evolve as strategy pair outcomes Cooperation-Cooperation, Defection-Cooperation or Defection-Defection at t to increase y at t+1, thus driving both positive and negative h, b and y feedback process through t+n iterations. These shape A^i variables, which allows adaptation to a changing environment, summing y_i, b_i, and h_i values. Feedback into subsequent A^{ij} game selection networks and strategy choice yields a complex adaptive system representation across multiple scales.

5 Results

I implement the agent-based model in NetLogo [28]. In this model, the entities that interact are all individual agents. The baseline initial population is 500 to represent a sample of any given population. The state variables for this model are fertility decision, education, and income. Global variables are level of instability and relative political capacity, which are setup at society level. Since society variables do not change on a daily basis, I approximate one time step as one month given data calibration [3][4] for a simulated time span of almost 20 years. This design allows me to study the dynamics of politics, economics, and demography of a society at with reasonable frequency, as most of the main variables do not change too often, and the 20 year period is also proper for a cycle in the study of political economy.

In order to make generalizable model inferences, I conducted a quasi-global sensitivity analysis on both input and initial condition parameters, for over 17,000 runs across 240 time steps. With income as the dependent variable, the result is shown in Table 1. Cooperation is measured as the number of agents who play cooperation strategy in the socio-economic transaction game, and defection is the number of agents who play defection. I track the number of transaction games as well as the number of agents in each iteration, and those two variables are presented as games and population below. The last variable, time, is simply the number of iterations in each run, distinguishing each month in each society's development process.

The first column presents the baseline model from POFED theory with only macro level variables. One can see that about 20% variance of aggregated income is explained by aggregated fertility rate, human capital, political instability, political capacity, population, time, and technology, which is presented as "talkspan", controlling for the distance within which individuals can reach to other individuals. It is presented here for me to compare the result of the other four models with individual level variables.

Column two, the first model on economic development first confirms POFED theory that negative value of instability do significantly speed the pace of economic development, with instability providing more substantive effect (β = -0.2269). It confirms the POFED theory that people are able to create more value in a stable environment. Looking at the impact of evolutionary games, we see the number of agents choosing cooperation has a significant positive impact (β = 2.3920) in increasing societal economic value, and it impact is much stronger than that of stability. This suggests that cooperation does pay higher social dividends on average. Talkspan spatial proximity is also positive and significant (β = 0.1071), confirming priors that increasing technology and compressing potential social space also speed development processes. In other words, increasing individual agents' ability to reach other like-minded agents spurs cooperation dramatically based on first order local interactions. This impact is even greater than that of cooperation strategy, suggesting technology development provides the sufficient condition for individuals to interact and create economic value. Time is slightly negative (β = -0.0411), indicating that economic prosperity is not self-reinforcing. Model fit (R^2=0.5432) is acceptable given the highly complex and non-linear dynamics and pooled nature of sensitivity analysis data. Compared to baseline model, adding individual choice of cooperative strategy increases model fit by 34%. In other words, this model captures the micro level behavior that can better explain macro level phenomena.

	(0) Income	(1) Income	(2) Income	(3) Income
Fertility rate	0.0470***	0.1223***	0.1331***	0.0324***
	(0.0032)	(0.0024)	(0.0024)	(0.0031)
Human capital	-0.0460***	-0.0067	0.0044	-0.0915***
	(0.0072)	(0.0054)	(0.0054)	(0.0071)
Instability	-0.0304*	-0.2269***	-0.2491***	-0.0026
	(0.0126)	(0.0095)	(0.0094)	(0.0124)
Political capacity	0.0121	0.0036	-0.0057	0.0292**
	(0.0111)	(0.0084)	(0.0083)	(0.0109)
Cooperation		2.3920***	2.1699***	
		(0.0079)	(0.0089)	
Defection			-0.3522***	
			(0.0067)	
Game				0.7777***
				(0.0121)
Population	-0.0896***			-0.4343***
	(0.0053)			(0.0075)
Talkspan	0.2792***	0.1071***	0.2275***	-0.0087
	(0.0017)	(0.0014)	(0.0027)	(0.0048)
Time	-0.0165***	-0.0411***	-0.0408***	-0.0153***
	(0.0010)	(0.0008)	(0.0008)	(0.0010)
_cons	0.3430***	0.3306***	0.3280***	0.5365***
	(0.0083)	(0.0059)	(0.0058)	(0.0087)
N	121035	121035	121035	121035
Adjusted R^2	0.2002	0.5432	0.5533	0.2265

Standard errors in parentheses
*** p<0.001",   ** p<0.01, * p<0.05

Table 1. Sensitivity Test Result

After confirming the positive impact of cooperative strategy, next I explore the impact of agents playing defection strategy at the same time. In the process of economic development, defective behavior has strong and negative impact (β = -0.3522), contrary to the positive impact of number of agents playing cooperation (β = 2.1699). Besides, defective strategy has stronger impact, in comparison to that of instability (β = -0.2491) and talkspan (β = 0.2275), the impact of which still hold in this model. Model fit (R^2=0.5533) increases marginally than model one, though we can still say both cooperative strategy and defective strategy significantly impact individual wealth and society wealth, adding more explanatory power to macro level dynamics.

The fourth columns focus on the number of interactions among individual agents and how that impacts the level of income. Not surprisingly, the variable games, indicating the number of societal economic transactions, positively influences wealth (β = 0.7777). In the process of individuals communicating and making deals with each other, more products and services become available while the cost of which goes down. This logic at the societal level is well discussed and empirically tested in globalization literature: in the process of increased interconnections among countries, benefits are derived from specialization of products and services, which outweighs the economic and social costs by achieving higher efficiency. Compared to the baseline model, this model contributes to explanatory power at a limited level, performing worse than the first two models, suggesting only counting for the number of interactions is not enough, what is more important is the type of strategy individuals choose when they interact with each other.

6 Conclusion

Combining both system dynamics, agent-based modeling and elementary games in a complex adaptive system, I formalize a simulation framework of the Politics of Fertility and Economic Development (POFED) to understand the relationship between politics, economic and demography change at both macro and micro levels. My results first confirm the findings of the POFED model at macro level, that political, economic and social factors are interrelated with each other. The sensitivity analysis provides more explanatory power to economic development. The number of individual interactions is critical to development. The more people interact with each other, the more value they can potentially create. However, besides the quantity of individual interactions, what matters most is individual agent’s strategic choice when they play socio economics transaction games. Cooperation does pay higher social dividends on average. Individual’s mutual cooperative behavior creates trust among each other, which enhances both political stability and economic growth. On the other hand, defection reduces social wealth, in addition to its negative impact to the level of trust in the society. Consistent with the findings from the macro POFED model, the model with micro inputs also shows increasing technology and compressing potential social space speed development processes. Macro level variables also feed back to individual agents updating their attributes and change the pace and tempo of socio-economic transactions, which reinforce national development and economic growth. In term of model fit, adding individual choice of strategies increases model fit by doubling that of the baseline model in which only macro inputs are taken into account. In other words, this approach that combines both levels captures the micro level behavior that can better explain macro level phenomena.

My innovative approach creates a baseline for current policy efforts, showing where and how instability or sustainable growth is likely to occur. Policy can then be tested compared to baseline outcomes, under normal and crisis scenarios, to assist in robust policy development. The strength of agent-based model is its ability of modeling interactions between individual agents and the environment, as well as emergent behavior and complexity of the entire system. In other words, ABMs provide a simulation framework for exploring multilevel modeling and interactive effects. A key benefit is understanding how macro structural environments change and constrain or incent individual micro-level behaviors, and how micro interactions shape macro structures.

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