Human Development Dynamics: An Agent Based Simulation of Social Systems and Heterogeneous Evolutionary Games

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Abstract. Combining a system dynamics and agent based modeling approach, we formalize a simulation framework of the Human Development (HD) perspective. We first capture the core logic of HD theory in a asymmetric, coupled nonlinear system with empirically validated parameters from World Values Survey (WVS) data. Using evolutionary game theory, second we fuse these endogenously derived individual socio-economic attribute changes with Prisoner's Dilemma in an agent based framework to model the interactive political-cultural effects of heterogeneous, spatial intra-societal economic transactions. We explore the model's behavioral dynamics via simulation methods to identify paths and pitfalls towards economic development, cultural plasticity, and social change behavior. Our preliminary results suggest strong nonlinear path dependence in three areas: development processes, evolutionary intra-societal transactions and development trajectories, with significant implications for anticipating and managing positive development outcomes.

Keywords: Economic Development, Cultural Shift, Democratization, Game Theory, Agent Based Model, System Dynamics

1 Introduction

The goal of this article is to extend previous work by Abdollahian et al. [1] on systems dynamic representation of HD theory within an agent based framework. We first instantiate a system of asymmetric, coupled nonlinear difference equations that capture the core logic of HD theory empirically validated with five waves of data from the World Values Survey (WVS). Second, we then fuse these HD endogenous individual attribute changes with a generalizable, non-cooperative Prisoner's Dilemma game following Axelrod [2-4], Nowak and Sigmund [24, 25], and Osterkamp [26] to simulate economic transactions. Understanding the interactive political-cultural effects of macro socio dynamics and individual agency in intra-societal transactions provides a new Human Development Dynamics model (HDD).

2 HD Dynamics Background

HD theory as posited by Ingelhart, Wetzel and others provides a framework in which economic modernization interacts with basic human needs and facilitates generalizable shifts in cultural predispositions and revolutionary behavior [17-19]. Empirical survey data suggest individual value orientations are represented by two primary dimensions— rational-secular and self-expression value orientations [17-19], [23], [32] which are shaped by economic progress and are more prevalent at different stages of economic development.

First, rational-secular values correspond to individuals' growing emphasis on technical, mechanical, rational, and bureaucratic views of the world. During the industrialization phase, cultural dispositions tend to progress from an emphasis on traditional pre-industrial values, measured in terms of religious ceremony attendance and the importance of religion, to secular world views, transferring authority from traditional religious figures to technological progress and bureaucratic political life.

The second dimension of self-expression corresponds to the post-industrial phase of economic development where economic progress and an advanced welfare system provide many individuals with an overwhelming sense of existential security [5]. As economic activity changes from primary, to secondary and tertiary sectors, the reduction in human constraint via increased productivity and wealth, advances in education, and service related economic activities, brings about a new sense of autonomy. Because the primary focus is no longer on survival, individuals are free to emphasize a general need for self-expression, question authority, and demand political participation. Rising self-expression values lead to the emergence of effective political institutions [30]. Mass tendencies toward self-expression facilitate a political climate conducive to elite-challenging activity and a civic culture consistent with democratic governance.

Self-expression values promote liberal political institutions through two mechanisms. First, to the extent that there is incongruence between cultural demand for liberal institutions and political supply of liberal institutions, individuals are more or less prone to elite-challenging activity, both violent and non-violent [16]. Second, self-expression values support the social acceptance of basic democratic norms such as trust and political participation. The result is a gradual transition toward democratization in autocratic nations and more effective political representation in democratic nations [19]. Declining economic conditions reintroduce the primacy of basic economic needs, fueling the structural conditions for more traditional value orientations, reducing society's ability to seek self-actualization, and increasing the likelihood of political revolution. More importantly, disequilibrium between culturally defined political expectations and political rights or civil liberty realities promotes elite challenging activity and

provides motivation for revolutionary change. Equations 1 through 4 outline HD's nonlinear, first order interdependent system [1].

$$\frac{dR}{dt} = \left[a_1 Y - a_2 (R - Y)\right] R(1 - R) \tag{1}$$

$$\frac{dS}{dt} = \beta_1 YS(1 - S) \tag{2}$$

$$\frac{dD}{dt} = \left[\gamma_1 S(S - D) + \gamma_2 D\right](1 - D) \tag{3}$$

$$\frac{dY}{dt} = \lambda_1 (1 - Y) + \lambda_2 D \tag{4}$$

R	rational-secular values
S	self-expression values
D	effective democracy
Y	economic progress

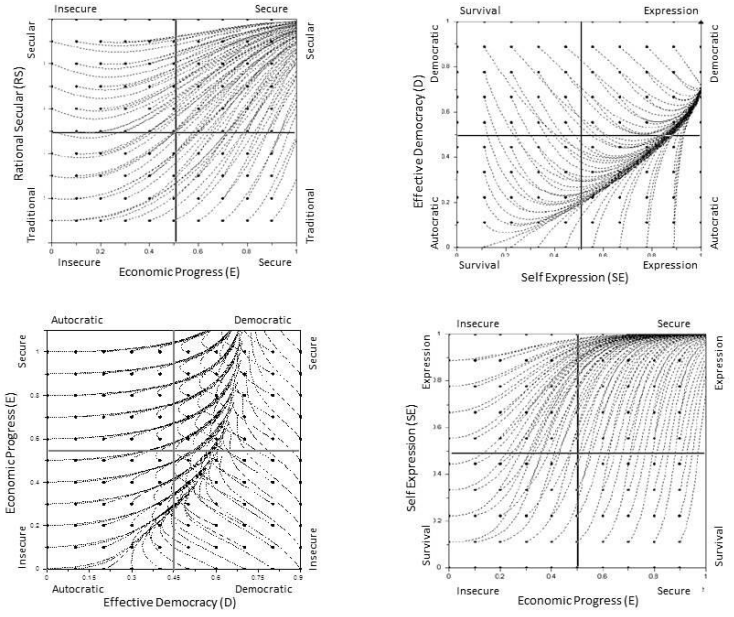

Figure 1: HD Phase Portraits **(**Abdollahian et al 2012**)**

Figure 1 above identifies four theoretically critical HD system phase portraits [1]. HD posits a staged process in which rising level of existential security via economic development leads to an increased emphasis on rational-secular and self-expression values. Specifically, individuals tend to emphasize rational-secular values during the industrialization phase of development and self-expression values during the post-industrial phase. Second, the rise in self-expression values strengthens democratic norms and promotes effective democracy, implying a positive relationship between self-expression and liberal political institutions. However, these effects are neither linear nor monotonic as we see strong reversion towards autocratic institutional preferences in low self-expressive, survival dominated societies. Lastly, based on work on liberal institutions and economic development [7], [10], [13], we expect positive feedback between democratic institutions and economic progress. Democratic norms and institutions that outpace economic progress are inherently unstable with a persistent, turbulent reversion process even at high levels of democratic norms and existential security. This suggests societies experiencing democratization can frequently expect punctuated reversals and revolutions towards more autocratic institutions until more sustainable democratic institutions re-emerge.

3 A Human Development Dynamics Model

Implemented in NetLogo [32], Figure 2 depicts the high level process and multi-module architecture. We maintain the individual agent attribute relationships and postulated changes of *R, S, D* and *Y* following the HD literature. These endogenously derived, individual agent attributes impact how economic transaction games occur, either increasing or decreasing individual wealth and ultimately societal productivity [6].

Capturing individual agent endogenous processes, we first transform Abdollahian et al. system of equations from differential to discrete equations for NetLogo tractability and use their empirically validated parameter values as a good first approximation. Given individual citizen attributes and HD processes at each timestep, we simply sum up each agent attributes across *Y, R, S* and *D* to find resulting societal distributions. This allows us to explore the effects of income inequality, cultural schisms, social complexity or highly polarized political institutions in any given society.

Evolutionary game theory provides insights to understanding individual, repeated transactions in heterogeneous populations [14], [20], [31]. In our case, we do not have well mixed populations, but explicit spatial contact networks given population density, technology diffusion and agent attributes recognizing that the differential impact of heterogeneous, spatial structures matters [27]. Accordingly, we instantiate a non-cooperative, socio-economic Prisoner's Dilemma transaction game given agent *i*'s (A*i*) political, social and cultural preference similarity to agent *j* (A*j*). The motivation behind this is that individuals are more likely to interact, engage and conduct transactions with other

agents of similar religious, secular and expressive norms [28].

At each *t*, we first randomly choose 50% of spatially proximal 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 neighborhood proximity distributions. Here we look at communications reach and technology diffusion as constraining the potential set of A*ij* game pairs, called talk span. Low values constrain games locally among spatially proximate agents while higher values expand potential A*ij* pairs globally, indicating socially compressed space.

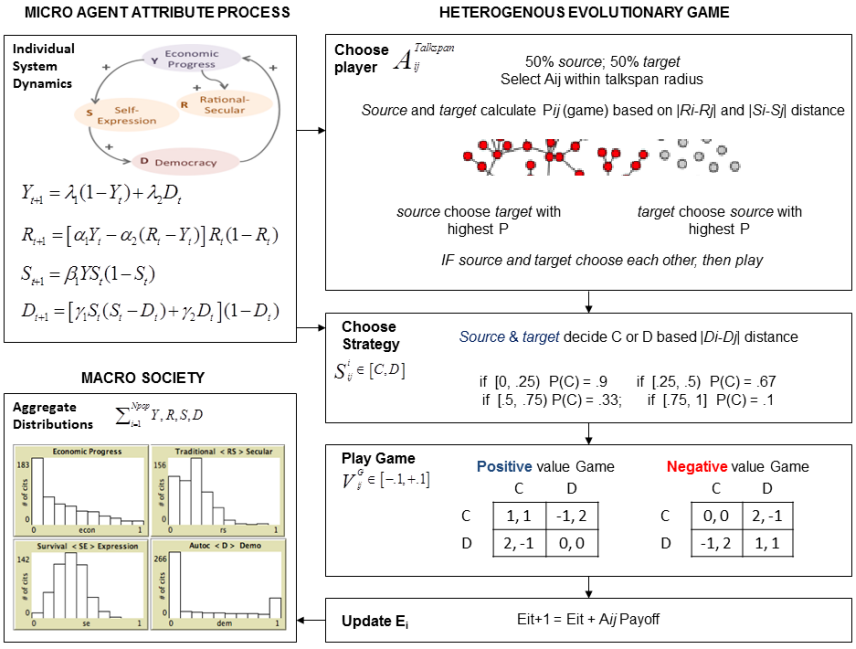

Fig. 2. HDD Architecture

Agent *i* evaluates the likelihood of conducting a simple socio-economic transaction with agent *j* based on similarity of socio-cultural preferences |*Ri-Rj*| and |*Si-Sj*| within a given local neighborhood. This captures communications and technology diffusion for frequency and social tie formation [21]. This also reflects recent work on the importance of both dynamic strategies and updating rules based on agent attributes[22].

Social Judgment Theory [9], [15] describes how the positions of two agents can be conceived along a Downsian continuum while distance between these positions affects the likelihood of one accepting the other's position. Source agents evaluate *S* and *R* distances separately between themselves and all target agents within a given talkspan neighborhood radius. Shorter preference distances

increase the probability that *Aij* will enter into a socio-economic transaction and play the PD game. 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. Target agents also repeat the same process symmetrically. We then choose the A*ij* pairing with the highest probability derived from its preference-proximity function as its partner at a particular iteration.

Agents probabilistically select strategies based on similarity of political preferences |*Di-Dj*|. Siero and Doosje [29] 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, capturing the notions of bipartisanship or conversely hyper-partisanship. So when *D* distance is short, there is a higher probability of cooperating while larger distances results in a higher probability of defecting. Relative payoffs for each agent is based on simple PD, non-cooperative game theory [11], [12], [24] where T > R > P > S, with T= 2, R=1, P = 0 and S= -1. When both agents cooperate, they gain TT; when one plays cooperate but the other plays defect, the cooperating one loses while the defecting one gains, yield ST; when both play defect, neither gain from the transaction, yielding PP, conditioned on an initially assigned game transaction value as below.

Following Nowak and Sigmund, we randomly assign game transaction values, however we do not asymmetrically constrain such values, instead allowing any particular transaction value V*ij* to lie in between [-.1, .1] to model different potential deal sizes, costs, benefits, or synergies for any agent to gain or lose. We explicitly model socio-economic transaction games as producing either positive or negative values as we want to capture behavioral outcomes from games with both upside gains or downside losses. Finally the A*ij* games' V*ij* outcomes condition agent *Ei* t+1 values, modeling realized costs or benefits from any particular pair. The updated $E_{it+1} = E_t + Aij\ Payoff_t$ subsequently gets added to agent *i's* individual attributes. We then repeat individual systems dynamics, aggregated up to society as a whole and repeat the game processes for t+n iterations.

4 Results

We use Abdollahian et al's parameter estimates from their genetic algorithm non-linear least squares (GANLS) estimation procedure on WVS data to populate system coefficients and conduct a quasi-global sensitivity analysis on both input and initial condition parameters for 700 time steps using pooled OLS regression. Here we approximate one time step as one month given past data calibration [1] for a time span of almost 60 years. The GANLS three step approach [8] first employs a genetic algorithm to search global parameter space, a simplex algorithm to search local parameters space, and finally a bootstrapping procedure to derive the uncertainty associated with the parameter estimates. We performed

over 40,000 runs given various input parameter combinations for a low resolution, initial sensitivity approximation.

Figure 3 depicts our HDD interface and a single sample run. The interface shows physical output space—heterogeneously mixed agents distributed spatially, where agent size indicates individual economic wealth *Y*, and color of agent represents democratic preference *D*, ranging from fully autocratic in red to fully democratic in blue. A*ij* game transactions at any *t* are shown as links. For all agent's *Y*, *R*, *S*, *D* attributes, we setup initial societal mean and standard deviation, population density and social connectivity via talkspan to simulate socio-technological conditions for any given society at any time.

Monitors and plots include time series and dynamic phase portraits for the societal average of *Y*, *R*, *S* and *D* trajectories and histograms across all attributes. This allows us to trace the development of wealth, income inequality, cultural dispositions, and political polarization. We also track the number of transactions games, the percentage of population interacting, and the number of different cooperative, mixed, or non-cooperative strategy pairs under different macro environmental conditions.

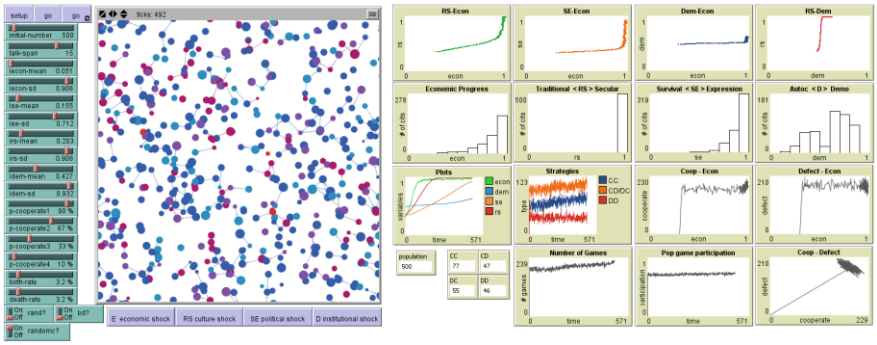

Figure 3: Sample HDD Run

4.1 Sensitivity Analysis

Table 1 details a sample of our quasi-global sensitivity analysis on the interactive parameter effects on economic prosperity *Y*, as well as strategy choice pairs CC, CD/DC and DD. We generated over 27 million observations and then randomly down-sampled to approximately 634,000 observations for pooled OLS tractability. As all variables are relatively scaled, we can interpret magnitude and substantive effects across β coefficients. Our first model on *Y* confirms HD theory that positive values of societal mean *R*, *S* and *D* values do significantly increase the pace of economic development, with *R* providing the most substantive impact (β = .3298). Looking at the impact of evolutionary games, we see that the number players both choosing cooperation has a stronger positive impact (β = .1606) than defection (β = .1088) in increasing societal economic

value, suggesting that cooperation does pay higher social dividends on average. Talkspan spatial proximity is positive and significant, confirming our priors that increasing technology and compressing potential social space interactions also speed development processes. Time is also slightly positive indicating that economic prosperity is quasi self-reinforcing. Model fit (R^2=.6441) is decent given the highly non-linear dynamics and pooled nature of sensitivity analysis data.

MODEL	Economic	CC	CD	DD
Economic		0.3846***	0.2467***	0.1032***
		(0.0019)	(0.0015)	(0.0015)
Rational Secular	0.3298***	-0.2756***	0.0598***	0.0643***
	(0.0022)	(0.0022)	(0.0020)	(0.0021)
Self Expressive	0.1488***	0.2139***	-0.0120***	-0.1571***
	(0.0015)	(0.0016)	(0.0014)	(0.0014)
Democratic	0.1161***	0.0623***	-0.0790***	-0.0337***
	(0.0016)	(0.0018)	(0.0015)	(0.0015)
Cooperate	0.1606***			
	(0.0006)			
Defect	0.1088***			
	(0.0011)			
Talk-span	0.1615***	0.5484***	0.3024***	0.1306***
	(0.0005)	(0.0010)	(0.0007)	(0.0007)
Time	0.0558***	0.1742***	-0.2414***	-0.1958***
	(0.0009)	(0.0013)	(0.0009)	(0.0007)
Constant	0.1972***	-0.2481***	0.0028*	0.1353***
	(0.0019)	(0.0017)	(0.0015)	(0.0016)
# of obs	634459	634459	634459	634459
Prob > F	0.0000	0.0000	0.0000	0.0000
R-squared	0.6441	0.6468	0.5171	0.3442
Root MSE	0.1285	0.2081	0.1500	0.1291

Numbers in parentheses are corresponding robust standard errors.
* Significance at 10% level. ** Significance at 5% level. *** Significance at 1% level

Table 1. Impact on Economic Development and Individual Strategy

Turning to HD parameter effects on heterogeneously mixed evolutionary games, we first focus on the conditions associated with CC strategy pairs. Talkspan is the most substantial (β = .5484), indicating increasing individual agents' ability to reach other like-minded agents spurs cooperation dramatically. Not surprisingly, economic progress *Y* (β = .3846) and self-expression *S* (β = .2139) are also influential on increasing cooperation societal transactions. Unexpectedly, secular values *R* (β = -.2756) significantly decrease societal cooperation, perhaps supplanting contract enforcement in traditional societies, while time (β = .1742) is positively significant showing how cooperation tends to evolve over time. This is especially interesting in light of *R*'s positive impact on growth, indicating that non-Pareto, asymmetric payoffs might be a necessary condition for development, regardless of path dependency.

Looking at the number of agent interactions with CD/DC strategy pairs, we

find the converse results. While talkspan still dominates (β = .3024) and the economic environment (β = .2467) influences the nature of strategic interactions, there is less relative impact in driving asymmetric agent strategies. Consistent with our previous results, increasing secular values *S* (β = .0598) slightly contributes to asymmetric strategic behavior while increasing democratic norms (β = -.0790) and expressive *R* behavior (β = -.0120) curtails such unilateral advantages. More importantly, time (β = -.2414) is highly negatively related to asymmetric payoffs as agents cannot sustain such transaction outcomes as preferences become closely aligned.

Finally, focusing DD strategy pairs, we find self expressive behavior (β = -.1571) and time (β = -.1958) have the largest impact in dampening asymmetric payoffs in societal transactions with democratic institutions D (β = -.0790) still deterring such behavior. Talk span (β = .1306) and economic progress *Y* (β = .1032) as expected increase DD strategy pairs but surprisingly at much lower levels than either in CD/DC or CC payoff transactions. Increasing the feasible spatial set and the wealth of individuals does increase the temptation to defect for both agents. Model fit (R^2=.3442) is relatively poor on DD strategy pairs compared to our other results, suggesting there are other processes which we need to further explore to increase result confidence.

4.2 Development Path Dependency

Figure 4 depicts a panel of average run trajectories across a sample of our parameter space. Here we focus on the interactive effects of low, medium and high self expressive ($\bar{S}$=.05, .5, .95) behavior plots across societies with differing low, medium and high democratic norms ($\bar{D}$=.05, .5, .95) for various levels of economic development and cooperative (CC) behavior. Each line represents the average of value at iterations between t_0 to t_{700} of our 40,000 runs, with low, middle and high developed ($\bar{Y}$=.05, .5, .95) societies trajectories in blue, orange and green respectively. Regardless of initial macro social conditions, we see both conditional sigma and beta income convergence with similar trajectory slopes only phase shifted. We also find cooperation does take time to emerge across all plots. However, focusing on highly developed societies (in green) across all plots, we see on average, intra-societal cooperative transactions emerge faster than for low income societies (in blue) although not necessarily at higher levels given our previous results which suggest income growth is a key driver of CC strategy pairs. Looking across initial democratic societal conditions, we find development outcomes and cooperative norms are most varied in low *S* societies that tend to disappear as individual and societal expressive culture increases. More interestingly, we see that democratic institutions actually provide the largest impetus fostering more cooperation and increasing growth in low and middle-income societies in all but highly expressive and democratic societies.

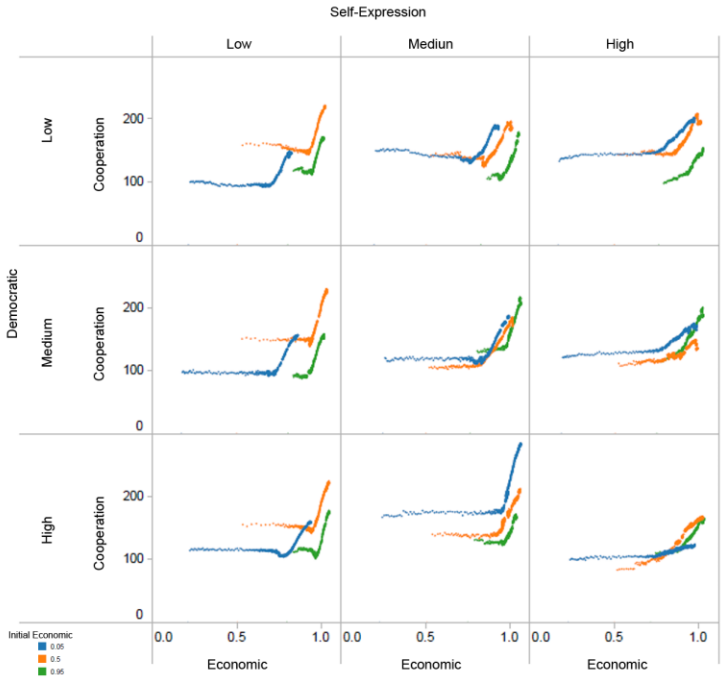

Figure 4: Path Dependency of 40,000 Average Run Trajectories across Parameter Space

5 Discussion

Consistent with HD theory, our model finds nonlinear path dependence in three areas: development processes, evolutionary intra-societal transactions and development trajectories. Economic progress is a necessary condition for successful secularization and expressive political behavior, which are antecedents for lasting democratic institutions. While modernization is not inevitable, we find a staged process where increasing existential security via economic development leads to greater emphasis on rational-secular and self-expressive values that results in societal development. Rational-secular norms strongly impact economic growth and speed up the pace of development more than self-expressive societal values alone. Also, mutual cooperation results in higher societal wealth than defection alone and is self-reinforcing over time.

Exploring the impact of societal conditions on evolutionary game outcomes, in CC strategy pairs, compressing social space by increased spatial proximity across society increases mutual cooperation dramatically. High secular values actually dampen CC outcomes indicates the necessary role of asymmetric, Nash dominant strategies as one potential engine of high growth during industrialization phases. For CD/DC strategy pairs, we find consistent and converse results. More

interestingly though, secular values and increasing time have a dampening effect on non-Pareto transaction outcomes while increasing societal wealth and expanding potential social connectivity increase poor DD outcomes initially.

Turning to the path dependence of development trajectories, our results are consistent with neo-classical growth income convergence. We find convergence despite various initial income levels, inequality, social and cultural conditions on both sigma levels and beta growth rates. We find Pareto outcomes as seen by CC strategy pairs, tend to emerge faster in low income countries then dissipate in high growth, middle income societies only to return towards more predominately Pareto transaction outcomes in high income societies. As such, Pareto outcomes and resulting wealth creation are most varied in low self-expressive societies. Democratic norms and institutions provide the largest impact in fostering cooperation and speeding economic growth in low and middle income societies. However, democratization benefits do diminish in advanced, highly expressive and already democratic societies when economics once again takes primacy.

While only a rough approximation at the truly interdependent and highly nonlinear nature of development, our HDD approach provides insights into the interactivity of individual agency and societal outcomes seen through the lens of evolutionary games. We hope such work motivates others to extend potential inquiries and insights with even higher theoretical fidelity and empirical resolution. Perhaps simulations such as HDD or other approaches can assist policy makers and scholar alike, to better understand, anticipate and shape more positive development outcomes.

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ODD Addendum

The model description follows the ODD (Overview, Design Concepts, and Details) protocol to document the fundamental processes of any agent based models (Grimm et al., 2006, 2010). The ODD framework provides a common ground for model overview, general concepts and detail model design, simulation, results and discussion. This makes any ABM relatively transparent, replicable and process knowledge transferrable to researchers across disparate fields and domains. The model is implemented in NetLogo (Wilensky, 1999) so we use some NetLogo conventions such as for pseudo code.

1. Purpose

The goal of our model is to help people understand the dynamic linkages between economic modernization, cultural change, and political development. We instantiate previous work (Abdollahian et al, 2012) on systems dynamic representation of HD theory within an agent based framework. HDD model fuses the interactive effects and feedbacks between heterogeneous, spatial intra societal economic transactions as well as macro constraints and opportunities implemented in NetLogo. We explore the model's behavioral dynamics via simulation methods to identify paths and pitfalls towards economic development, cultural plasticity, and social change behavior.

2. Entities, state variables, and scales

HDD has three entities, grid cells, individual agents and agent links.

The first entity represents the environment where agents interact with each other. One grid cell represents 10 square meters and the model landscape comprised 200 x 200 km^2. State variables include population size and thus density, as well as talkspan (the distance within which individuals talk with each other).

The second entity—individual agents, are characterized by several state variables including location, economic condition, rational-secular, self-expression, and democratic value. The last four variables interact with each other in agent endogenous process defined by a system of discrete equations- Rational-secular is a function of its past value and economic condition; Self-expression is a function of its past value and economic condition; Democratic value is a function of its past value and self-expression; Economic condition is a function of its past value and democratic value. Probability of having a cooperative strategy is calculated by the distance between two agents' democratic value.

The third entity are agent links, which identify at each tick whether or not agents

participate in a non-cooperative economic game transaction.

The time step in HDD is one month per tick; simulations are usually run 700 months coinciding with the Human Development theory's multi-generational timescale.

3. Process overview and scheduling

HDD model has two sequential processes, a systems dynamic agent endogenous updating process and an evolutionary game process. Figure 1 depicts the architecture with these two processes. In the agent endogenous process, agents update individual attributes: economic condition, rational-secular, self-expression, and democratic value. We transform Abdollahian et al. system of equations from differential to discrete equations for NetLogo tractability and use their empirically validated parameter values as a good first approximation.

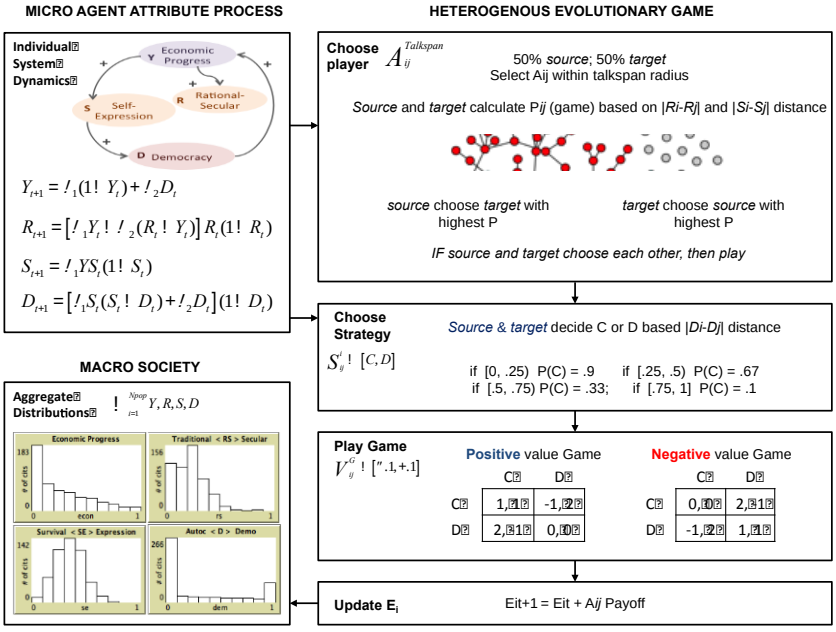

Fig. 1. HDD Modules

In our heterogeneous evolutionary game process, agents play a non-cooperative, socio-economic Prisoner's Dilemma transaction game. At the beginning of this process, we first randomly choose 50% of the agents to be source who can choose a partner, and the rest to be the target that can be chosen by the source agents.

The source agents first find all target agents within a radius determined by talkspan, then calculate the difference between rational-secular and self-expression with all of them. In the next step, both the source and target agents calculate the probability of playing the transaction game—the larger the difference between their rational-secular and self-expression, the lower probability this pair of agents will play the game. If the probability is below 0.05, agents will simply choose not to play. Otherwise, if the source and the target agents choose each other, they will actually play at tick t. After deciding to play, source and target agents will choose cooperate or defect strategy, based on the distance between the pair's democratic value. The smaller the distance is, the higher probability they will play cooperate. Lastly, agents play the Prisoner's Dilemma transaction game and the payoff is reflected on their economic condition, which goes back to agent endogenous updating process for the next iteration. The pseudo-code for the two modules can be written as:

```
To endogenous process
  Ask agents update four endogenous attributes
End

To play PD transaction game
  Ask random 50% of the agents be source and the rest be target
  Ask source agents create links to target agents within talkspan
  Ask links calculate distance between RS and SE and probability of playing game
  If probability < 0.05 [ask link die]
  Ask source agents keep the out-link with highest probability and kill other out-links
  Ask target agents keep the in-link with highest probability and kill other in-links
  Randomly set game value
  Ask both ends of a link to calculate the distance between D and probability of playing
cooperate and defect
  Ask both ends to choose strategy
  Ask both ends calculate payoff from game value and strategies of CC/CD/DC/DD
  Ask both ends to update E based on the payoff from the game
End
```

4. Design concepts

Emergence. Individual agents update endogenous attributes given the initial mean and standard deviation of the society. With different talkspan, we see dynamic changes in individual strategies as well as the individual economic wealth generated from game payoffs. These emergent behaviors impact agents' endogenous process in the next iteration.

Adaptation. Agents choose whether to play the transaction game based on their location and talkspan. The larger talkspan, the more people they can choose from—only when the difference between their self-expression and rational-secular values is small enough will they play a game. Agents are also adaptive when they choose strategies based on the calculation of the difference between their democratic values. Each agent has initial democratic value and this value is updated every tick with a function of its past value and self-expression.

Objectives. Agents make decisions on whether to play a game by ranking probabilities of playing a game with all possible partners. The more similar their self-expression and rational-secular is, the higher probability they will play a game with each other. Each agent will sort the probability of playing a game with all possible partners and choose the partner with the highest probability to play. Similarly, agents also make strategic decisions based on the probability of playing cooperation. Similar democratic values between two agents lead to high probability of playing cooperation.

Prediction. Each agent predict his probability of playing a game with each possible partner within radius of talkspan based on their rational-secular and self-expression distance. They make their decision based on proximity and those ideological distances. They also predict their probability of playing cooperation if they decide to play a game. This probability is calculated based on the distance between democratic values of the pair of agents.

Sensing. Each agent senses the distance between other agents and four endogenous variables of those agents. Observer can report the mean of those endogenous variables from the entire population.

Interaction. Agents directly interact with each other through a PD transaction game. Based on the strategies agents choose, each interaction can result in different payoffs that changes in both agents' economic condition. Relative payoffs for each agent is based on simple PD, non-cooperative game theory where $T > R > P > S$.

Stochasticity. HDD model use stochasticity in assigning a game value, which can be positive or negative. Agents calculate payoffs based on strategies and game value, which impacts their individual economic wealth.

Collectives. Agents form pairs and play games, impacting their economic condition, but they act individually.

Observation. We generate output time series and dynamic phase portraits for the societal average of economic condition, self-expression, rational-secular, and democratic value trajectories. We also output histograms across all macro social attributes, showing total societal density distributions for income inequality, growth, cultural dispositions, and political polarization. Number of transactions games, the percentage of total population interacting, and the number of different cooperative, mixed, or non-cooperative strategy pairs under different macro environmental conditions are also observed.

5. Initialization

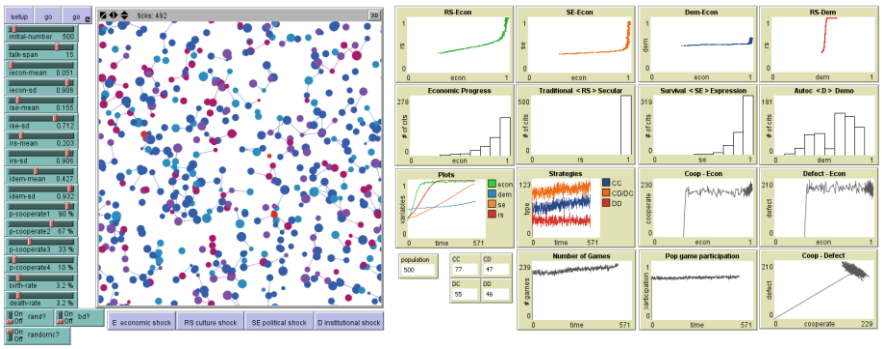

Fig. 2. HDD Interface

HDD is initialized with individual agents based on the input number of population, which given the fixed 200x200 grid size, allows us to model density. Agents are randomly allocated to patches, and are assigned with initial value of economic condition, rational-secular, self-expression, and democratic value, with global mean and standard deviation weighted in the range of [0, 1].

Figure 2 shows the NetLogo interface. We represent individual agents as dots, which are sized by individual economic wealth. The color is set by five ranges where blue indicates highest level of democratic norms and red indicates the lowest level. On the left side are sliders to control model parameter settings and input data. Besides global mean and standard deviation of four endogenous attributes, we also control for the probability of playing cooperation. On the right

side of the dashboard, we display several monitors and plot windows.

The initial state of the model includes 500 agents, with global mean of all endogenous variables set at 0.5 and standard deviation at 0.5 as well. The probability of playing cooperation is 0.9 if the democratic value distance is less than 0.25, 0.67 if the distance is between 0.25 and 0.5, 0.33 if the distance is between 0.5 and 0.75, and 0.1 if the distance is greater than 0.75. Initialization can vary among simulations.

6. Input data

The model does not use input data to represent time-varying processes.

7. Submodels

7.1 Agent Endogenous Process Submodel

The agent endogenous process submodel focuses on the four attributes. We transform Abdollahian et al. system of equations from differential to discrete equations for NetLogo tractability and use their empirically validated parameter values as a good first approximation. Given individual citizen attributes and HD processes at each timestep, we simply sum up each agent attributes across the four attributes to find resulting societal distributions for each variable. This allows us to explore the effects of income inequality, cultural schisms, social complexity or highly polarized political institutions in any given society as the resulting sum of individual efforts. Equations 1 through 4 outline HD's nonlinear, first order interdependent system (Abdollahian et al 2012:6).

$$\frac{dR}{dt} = \left[a_1 Y - a_2 (R - Y)\right] R(1 - R) \quad (1)$$

$$\frac{dS}{dt} = \beta_1 YS(1 - S) \quad (2)$$

$$\frac{dD}{dt} = \left[\gamma_1 S(S - D) + \gamma_2 D\right](1 - D) \quad (3)$$

$$\frac{dY}{dt} = \lambda_1(1-Y) + \lambda_2 D \quad (4)$$

R	rational-secular values
S	self-expression values
D	effective democracy
Y	economic progress
α_1	maps the interactive effects of Y and R onto growth in level of R
α_2	regulates the dynamic effects of economic incongruence
β_1	maps the interactive effects of Y and S onto growth in the level of S
γ_1	regulates the dynamic effects of political incongruence
γ_2	maps past governance structure onto the growth in effective democracy
λ_1	parameter for economic progress
λ_2	parameter of the democratic impact on economic development

7.2 Heterogeneous Evolutionary Game Process Submodel

In the heterogeneous evolutionary game process, agents are playing a non-cooperative, socio-economic Prisoner's Dilemma transaction game. At the beginning of this process, we first randomly choose 50% of the agents to be source who can choose a partner, and the rest to be the target that can be chosen by the source agents. The source agents first find all target agents within a radius determined by talkspan, then agent *i* evaluates the likelihood of conducting a simple socio-economic transaction with agent *j* based on similarity of socio-cultural preferences |*Ri-Rj*| and |*Si-Sj*|. If the likelihood is below 0.05, the agents will simply choose not to play a game. Otherwise, if the source and the target agents choose each other, they will actually play the transaction game.

After agents decide to play, each select strategies probabilistically based on similarity of political preferences as expressed by |*Di-Dj*|. The probability of playing cooperation is 0.9 if the democratic value distance is less than 0.25, 0.67 if the distance is between 0.25 and 0.5, 0.33 if the distance is between 0.5 and 0.75, and 0.1 if the distance is greater than 0.75.

Lastly, agents play the Prisoner's Dilemma transaction game with game value in the scale of [-0.1, 0.1]. Relative payoffs for each agent is based on simple PD, non-cooperative game theory (Nowak and Sigmund 1994, Dixit et al 2009). If the game value is positive, when both agents play cooperation, their payoffs are +

game value; when one plays cooperation and one plays defect, their payoffs are – game value and + game value * 2; when both play defect, their payoffs are 0. If the game value is negative, when both agents play cooperation, their payoffs are 0; when one plays cooperation and one plays defect, their payoffs are + game value * 2 and - game value; when both play defect, their payoffs are + game value. These payoffs are reflected in agents' economic condition, which goes to agent endogenous process in next iteration.

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