Innovation and Structural Change in Complex Evolutionary Systems

Part III
Agent Based Models

Tommaso Ciarli

SPRU, University of Sussex
t.ciarli@sussex.ac.uk

XIX Escuela de Verano de la CEPAL Sobre Economías Latinoamericanas
División de Desarrollo Productivo y Empresarial, CEPAL
Santiago, August 13-17, 2018
Plan for the next four of days

Part I: discuss some evidence and main properties of innovation (as an evolutionary process)

Part II: discuss some evidence and main properties of complex systems

Part III: introduce the use of ABM to study complex economic systems – taster of ACE

Part IV: modelling micro aspects of innovation
  - The basic evolutionary process: replicator dynamics
  - Search: NK Model
  - Path dependency: technological choice

⇒ Part V: model growth and structural change as an evolutionary complex dynamic
Agent based models

Part III
Alternative modelling tools: agent based models
Plan for Part III

- Why ABM: summary of evolutionary complex systems
- Definition and properties
- Implementation and structure of an ABM
Main references

- [http://www2.econ.iastate.edu/tesfatsi/ace.htm](http://www2.econ.iastate.edu/tesfatsi/ace.htm)
**Summary**

<table>
<thead>
<tr>
<th>Innovation and evolution</th>
<th>Complex systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamics</td>
<td>Evolution</td>
</tr>
<tr>
<td>Knowledge</td>
<td>Accumulation &amp; heterogeneity</td>
</tr>
<tr>
<td>Clustering</td>
<td>Accumulation &amp; discrete changes</td>
</tr>
<tr>
<td>Trajectories</td>
<td>Path dependence &amp; nonlinearity</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>Risk / high variance</td>
</tr>
<tr>
<td>Heterogeneity</td>
<td>Evolutionary / sectors</td>
</tr>
<tr>
<td>Interactions</td>
<td>Diffusion, imitation, selection</td>
</tr>
<tr>
<td>Interdependence</td>
<td>Systems</td>
</tr>
<tr>
<td>Limited rationality</td>
<td>Heuristics</td>
</tr>
</tbody>
</table>
Empirical evidence suggests heterogeneity, skewed distributions (average not useful), cumulation & clustering, uncertainty, limited rationality, evolution, interactions (systems), non linearities, use of routines

Innovation

- is persistent, dynamic (and follows a trajectory), highly uncertain
- uses innovation, knowledge, learning – in non linear way
- generates several responses, heterogeneity (structural change), more innovation, imitation, adaptation
- differs across populations – industries and consumers

⇒ inherent features of evolutionary complex systems (not of standard economic models)
Main problems in standard macroeconomics

Focussed on atomistic behaviour with no interactions
Use of static equilibrium
Little investigation on the evolution towards equilibrium
Information transmission (e.g. contagion) assumed away

Holds on two crucial assumptions:
- rationality of individuals (widely criticised from Simon onwards)
- aggregate behaving like a “rational individual”

Economic structure is lost under aggregation

Most relevant stylised facts cannot be reproduced (Fagiolo and Roventini, 2012, 2017; Haldane and Turrell, 2018)
The distribution of year-on-year growth in GDP, 1871–2015

Source: Haldane and Turrell (2018)
Problems with standard economic models

Range of GDP forecasts (27 forecasters) in 2007Q4 – UK

Source: https://www.bis.org/review/r161115a.pdf
‘[T]here is also a strong belief, which I share, that bad or rather over-simplistic and overconfident economics helped create the crisis. There was a dominant conventional wisdom that markets were always rational and self-equilibrating, that market completion by itself could ensure economic efficiency and stability, and that financial innovation and increased trading activity were therefore axiomatically beneficial”

Adair Turner, Ex Chairman of the Financial Services Authority, U.K
## Comparing Economic models and Complex Systems (G. Fagiolo)

<table>
<thead>
<tr>
<th></th>
<th><strong>Standard Economic models</strong></th>
<th><strong>Complex Evolving Systems</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Individuals</strong></td>
<td>1,2 or infinite, fully rational, sophisticated learning</td>
<td>N large but finite, simple entities, adaptive, routine behaviour</td>
</tr>
<tr>
<td><strong>Interactions</strong></td>
<td>Extreme cases, trivial patterns (full or empty/star graphs)</td>
<td>Non trivial patterns, local interactions with subset of other agents</td>
</tr>
<tr>
<td><strong>Diversity</strong></td>
<td>Possibly heterogeneous, but diversity does not matter for aggregate dynamics</td>
<td>Persistently heterogeneous, diversity matters for aggregate dynamics</td>
</tr>
<tr>
<td><strong>Time and Aggregate Dynamics</strong></td>
<td>Static (not truly dynamic) models, only equilibrium states count</td>
<td>Truly dynamic systems, equilibria possibly irrelevant, meta-stable states and emergent (self-organized) properties</td>
</tr>
</tbody>
</table>
Why simulations?

In order to analyse complex social problems (e.g. development and environmental sustainability) we need a different class of models that can

- Embed realistic assumptions into micro and macro models: uncertainty, procedural decision, heterogeneity, local interactions, non-equilibrium
- Replicate some of the empirical evidence discussed
- Include innovation and structural changes
- Do not assume macro dynamics

“Agent-based models [...] are suited to answering macroeconomic questions where complexity, heterogeneity, networks, and heuristics play an important role” (Haldane and Turrell, 2018, p. 219)
Why simulations?

Interaction of objects (agents) as a complex problem $\implies$ no analytical solution

Social interaction as a complex problem with individual behaviour (less straightforward then physical behaviour)

- No closed system
- Interaction of heuristics and reaction heuristics

“I can calculate the motion of heavenly bodies, but not the madness of people” (I. Newton)

Simple interactions can lead to complex outcomes (Arthur, 1994; Schelling, 1971)

- Minority games, urban segregation, choice of a technology/good
- The place where you are sitting now
Schelling segregation model: explaining segregation

Micromotives and Macrobehaviour (Schelling, 1978): segregation can be explained by the interaction of simple individual choices (no racism...)

(a) Stay if at least 1/3 of neighbours are ‘kin’

(b) Move to random location otherwise

Source: L-E Cederman
Schelling segregation model: set-up

N agents located on a 2-dimensional grid (torus) of $L \times L$ cells.

Types: Each agent can be either RED or GREEN

Only a percentage $p$ of cells is occupied: $N < L \times L$

Agents are initially located on the grid at random

In each time period, agents may be happy or unhappy

Agent cares about the proportion $q$ of other agents of same colour in its Moore neighbourhood of radius 1

Agents are unhappy if $q$ is below a certain critical threshold (parameter of the model) and happy otherwise

In each iteration of the model one unhappy agent is randomly selected to move to a random empty cell in the lattice
Schelling segregation model: experiments

*Source*: Izquierdo et al. (2009)

http://jasss.soc.surrey.ac.uk/12/1/6.html
Schelling segregation: Chicago 1940

Source: Möbius and Rosenblat (2001)

Percentage of blacks: 1-5% yellow; 5-10% pink; 10-25% orange; 25-50% red; 50-75% dark red; 75-95% brown; > 95% black
Schelling segregation: Chicago 1950

Source: Möbius and Rosenblat (2001)

Percentage of blacks: 1-5% yellow; 5-10% pink; 10-25% orange; 25-50% red; 50-75% dark red; 75-95% brown; > 95% black
Modelling an evolutionary complex system

Schelling segregation: Chicago 1960

Source: Möbius and Rosenblat (2001)

Percentage of blacks: 1-5% yellow; 5-10% pink; 10-25% orange; 25-50% red; 50-75% dark red; 75-95% brown; > 95% black
## ACE: Definition

**ACE**

Agent–Based Computational Economics: “the computational study of economic processes modelled as dynamic systems of interacting agents” (L. Tesfatsion)

Modeller constructs a virtual economic world populated by various agent types (economic, institutional, social, biological, physical)

Modeller sets initial world conditions

Modeller then steps back to observe how the world develops over time (no further intervention by the modeller is permitted)

World events are driven by agent interactions
Main properties of ACE

Population of *heterogeneous* (economic) ‘agents’

Agents live in complex systems evolving through time (Kirman, 1998). True dynamics: non reversible

No ‘hyper-rationality’ (Dosi et al., 1996): internal states, rules of behaviour, and adaptive expectations

Agents are autonomous or semi–autonomous

Agents interact with one another and possibly with an environment (local/social interactions)

Endogenous and persistent novelty (technological change): open-ended system

*Aggregate structure emerges from agent interactions* (Tesfatsion, 1997)

*Generations of agents emerge from the interactions of their ancestors* (selection, retention, innovation ‐> evolution) (Nelson and Winter, 1982)
### Structure of ABM

<table>
<thead>
<tr>
<th>Elements and structure</th>
<th>Time</th>
<th>Sets of Agents</th>
<th>Sets of Micro States</th>
<th>Vectors of Micro-Parameters</th>
<th>Vector of Macro-Parameters</th>
<th>Interaction Structures</th>
<th>Micro Decision Rules</th>
<th>Aggregate variables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Elements and structure</strong></td>
<td><strong>Time</strong></td>
<td><strong>Sets of Agents</strong></td>
<td><strong>Sets of Micro States</strong></td>
<td><strong>Vectors of Micro-Parameters</strong></td>
<td><strong>Vector of Macro-Parameters</strong></td>
<td><strong>Interaction Structures</strong></td>
<td><strong>Micro Decision Rules</strong></td>
<td><strong>Aggregate variables</strong></td>
</tr>
<tr>
<td><strong>Time</strong></td>
<td>$t = 0, 1, 2, \ldots, (T)$</td>
<td>$l_t = 1, 2, \ldots, N_t$</td>
<td>$i \rightarrow x_{i,t}$</td>
<td>$i \rightarrow \theta_i$</td>
<td>$\Theta \in \mathbb{R}^m$</td>
<td>$G_t \in \mathcal{P}(l_t)$</td>
<td>$R_{i,t}(\cdot</td>
<td>\cdot)$</td>
</tr>
</tbody>
</table>

**Discrete**

- Often $N_t = N$
- Firm’s output
- Res. Wage
- Min. Wage
- Networks
- Innovation rule
- GNP

*Source: by courtesy of Giorgio Fagiolo*
Evo complex approach builds from bottom up (interacting agents)

Source: Page (2015)
Realisations

Highly parametrised: analysis
  - Parameters of interest: functional analysis
  - Whole space / reasonable space

Stochastic processes
  - Uncertainty: sequence of stochastic events can have a strong effect on the outcome (e.g. percolation)
  - Analyse distribution of each output variable

Each realisation a scenario (consistent with the model and in probability)
Analysis of plausible scenarios
Calibration

- Abstract model vs explanation of a phenomenon vs foresight

Reproducing empirical evidence, under given parameter values (validation)

Robust assumptions: based on empirical evidence
Procedure of ABM

Initial Conditions: $(x_{i,0})$
Micro & Macro Pars: $(\theta_i), \Theta$

Generate Time-Series through Simulation
\{(x_{i,t}), t = 1, \ldots, T\}
\{Y_t, t = 1, \ldots, T\}

Compute a Set of Statistics
$S = \{s_1, s_2, \ldots\}$
on micro/macro Time-Series

Repeat M ind. times

Source: G. Silverberg
Some applications in economics and business

- Evolutionary-Games: P. Young, Kandori et al., Blume, Ellison
- (Local) Interaction Models: Kirman, Weisbuch, Lux
- Endogenous Network Formation: Vega-Redondo, Cowan, Goyal, Jackson-Watts...
- Innovation (Polya-Urn Schemes): Arthur, Dosi, Kaniiovski, Lane, Marengo
- Complexity: Frenken, Valente, Marengo
- Strategy and organisations: Carley and Pietrula, Lomi and Larsen
- Technological modularity, firm and industry organisation: Ethiraj et al. (2007); Frenken et al. (1999); Kauffman et al. (2000); Marengo and Dosi (2005); Ciarli et al. (2008)
Some applications in economics and business

- Growth: Nelson and Winter (1982), Silverberg, Verspagen, Dosi, Howitt, Llerena and Lorentz (2004); Dawid and Fagiolo (2008); Dosi et al. (2010); Ciarli et al. (2010); Ciarli (2012); Ciarli et al. (2012); Fagiolo and Roventini (2012)
- Firms location: David et al. (1998)
- Firms and technological change: Dawid (2006); Teitelbaum and Dowlatabadi (2000); Yildizoglu (2002)
- Electricity markets: Tesfatsion
- Sectoral studies: Malerba et al
- Environmental economics: van den Bergh, Safarzynska, Windrum et al. (2009a,b)
Some applications in economics and business

- Industrial life cycle cycles: Windrum and Birchenhall (2005), Malerba et al
- Labour market: Tesfatsion, Fagiolo et al. (2004), Richiardi and Leombruni
- Financial markets (a huge number): Delli Gatti et al. (2004), Delli Gatti and Stiglitz, Cont, econophysics
- Macro instability: Bak et al. (1993); Dosi et al. (2006), Weisbuch and Battiston, Ciarli and Valente (2007)
- Macro: Howitt, Duffy, Arifovic
- Firms coalition and network formation: Cowan and Jonard, Ozman, Page, Huberman, Axtell, Vega-Redondo, Jackson, Watts
- Foresight: Lempert
- Other social sciences: Politics (state cooperation, conflict), Sociology, Anthropology, ...


References III


