Innovation and Structural Change in Complex Evolutionary Systems

Part IV

Examples of basic micro 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

Examples of micro models

Part IV:
Example of micro models on evolutionary dynamics, search on a complex landscape, and path dependence

Plan for Part IV

- The basic evolutionary process: replicator dynamics
- Search: NK Model
- Path dependency: technological choice
- Application to the risk-reward nexus – who pays and benefits from innovation

Main references

- Arthur, W Brian (1989). Competing Technologies, Increasing Returns and Lock-in by Historical Events. *Economic Journal* 99: 116-31.
- Dawid, H. (2006). Agent-Based Models of Innovation and Technical Change. In L. Tesfatsion & K. L. Judd (Eds.), Handbook of Computational Economics, Volume 2: Agent-Based Computational Economics (pp. 1235–1272). North-Holland
- Metcalfe, J. Stan (1994). Competition, Fisher's Principle and Increasing Returns in the Selection Process. *Journal of Evolutionary Economics* 4 (4): 327-46.
- Safarzyńska, K., & van den Bergh, J. C. J. M. (2010). Evolutionary models in economics: a survey of methods and building blocks. Journal of Evolutionary Economics, 20(3), 329–373
- Valente, Marco (2014). An NK-like Model for Complexity. *Journal of Evolutionary Economics* 24 (1): 107-34
- Wirkierman, Ariel L., Tommaso Ciarli, and Mariana Mazzucato (2018). An Evolutionary Agent-Based Model of Innovation and the Risk-Reward Nexus. SPRU, University of Sussex, Brighton, UK.

The market

Market: two populations

Firms: produce and modify their competitive position intentionally (by innovation) or not (by learning)

- Good's quality
- Different production process (and cost)

Use existing and accessible knowledge to intentionally innovate

- From science
- From previously cumulated knowledge
- From other firms: imitation

Consumers: select on price and quality

- Price lies between costs and product value

Market evolution

Firms (loosely) refer to prospective and actual profits/sales to decide investment

Consumers change supplier if the new one offers greater value for money

Differences in profitability might determine different firm growth rates (Profitability $\rightarrow$ Investment $\rightarrow$ Growth)

- Industrial dynamics and structural change

"Firms compete by being different, by expressing individuality, and the role of the market process is to translate those differences into a pattern of change. [...] Evolutionary competition is a process, not a state of affairs; it is a matter of changing order and structure, not of equilibrium" (Metcalfe, 2014, p. 31)

A note on consumer behaviour

Consumers are also heterogeneous.

Goods have different characteristics (Saviotti and Metcalfe, 1984) and dimensions and meet different needs and wants (Valente, 2012)

Compounding the (intertemporal) utility of all dimensions in one preference indicator is too difficult (Sen, 1980)

Consumers tend to use quite simple heuristics (Kahneman and Tversky, 2000)

Consumer's preferences change

- Learning (Witt, 2001)
- Social adaptation and "upgrading" (Aversi et al., 1999)
- Networks (epidemic)
- Advertisement

Replicator dynamics

Basic evolutionary model

Evolutionary dynamics

- Constant change: innovation
  - Agents
  - Environment
- Competing agents and competing populations: selection
- The agents that better adapt to the environment, contribute to define the environment
- Accumulation: the fittest become fitter (incremental changes)

⇒ Evolutionary process: “Economic variation is the outcome of innovation and selection is the means by which the economy adapts to variety” (Metcalfe, 2014, p. 29)

Basic evolutionary process (Metcalfe, 1994)

Population of firms

Homogeneous good

Perfect market competition

Firms invest an identical proportion of profits to increase capacity: f

Given price: p

Heterogeneous cost (technology): h_i

$\Rightarrow$ Firm growth rate

$$g_i = f(p - h_i)$$

Basic evolutionary process (Metcalfe, 1994)

Population average unit cost (technology)

$$\bar{h}_s = \sum s_i h_i$$

where s_i is the market share of firm i

Population average growth rate (profitable firms)

$$g_s = \sum s_i g_i$$

Variation of market shares (replicator dynamics)

$$\frac{ds_i}{dt} = s_i \left(g_i - g_s \right) = f s_i \left(\bar{h}_s - h_i \right) \tag{1}$$

Basic evolutionary process (Metcalfe, 1994)

Two categories of firms

- Growing but losing market shares: $p > h_i > \bar{h}_s$
- Growing and increasing market shares: $p > \bar{h}_s > h_i$

How does the population's technology change (cost)?

$$\frac{d\bar{h}_s}{dt} = \sum_i \frac{ds_i}{dt} h_i = Cov_s\left(h_i, g_i\right) \tag{2}$$

"The rate of change of the mean is proportional to the (share weighted) covariance between unit costs and rates of growth at the firm level." (Metcalfe, 1994, p. 332)

p-NK

Innovation on a complex landscape

Firm innovating in a competing market

Use search routines constrained by technological capabilities and paradigms, and a limited knowledge of the present world and competitors

- Learn to search

Limited knowledge of the technological space: lock-in in local optima

NK model (Kauffman and Levin, 1987)

The fitness (F) of a system depends only on the interaction structure among its elements and on their mutation strategy

Each element $i \in N$ is connected to K other elements

Each element i has a fitness contribution f

- Independent from other elements ($K = 0$)
- Dependent on other elements

K (interactions) defines complexity (product decomposability (Simon, 2002))

pNK structure (Valente, 2014)

The fitness function $f(\vec{x}) : \vec{x} \in \Re^N \rightarrow [0, M]$ is defined as the average of N dimensions' fitness contributions $\phi_i(\vec{x})$, one for each dimension i of the problem/technology space:

$$f(\vec{x}) = \frac{\sum_{i=1}^{N} \phi_i(\vec{x})}{N}$$

$$\phi_i(\vec{x}) = \frac{M}{(1 + |x_i - \mu_i(\vec{x})|)}$$

$$\mu_i(\vec{x}) = c_i + \sum_{j=1}^{N} a_{i,j} x_j$$

pNK structure

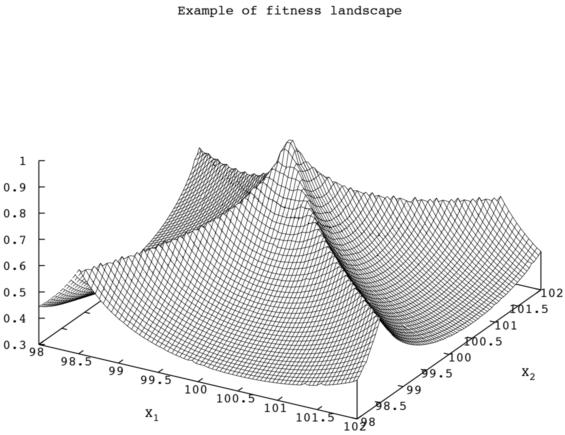
$$f(\vec{x}) = \frac{\sum_{i=1}^{N} \phi_i(\vec{x})}{N}$$

$$\phi_i(\vec{x}) = \frac{M}{(1 + |x_i - \mu_i(\vec{x})|)}$$

$$\mu_i(\vec{x}) = c_i + \sum_{j=1}^{N} a_{i,j} x_j$$

Parameter M determines the maximum fitness value.
Variable c_i determines the position of the global optimum $\vec{x}^* = \{x_1^*, x_2^*, ..., x_N^*\} : f(\vec{x}^*) = \sum M/N$.
$c_i = x_i^* - \sum_{j \neq i} a_{i,j} x_j^*$
The coefficients $a_{i,j} \in [0, 1]$ determine the influence of dimension j on the contribution of dimension i.

2-D *pNK* landscape

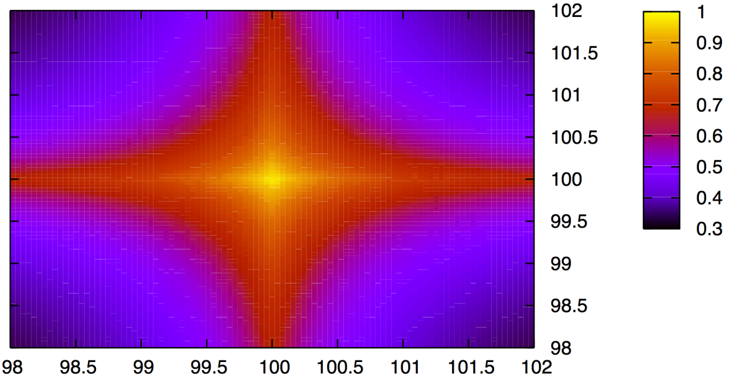


One-dimensional search strategy

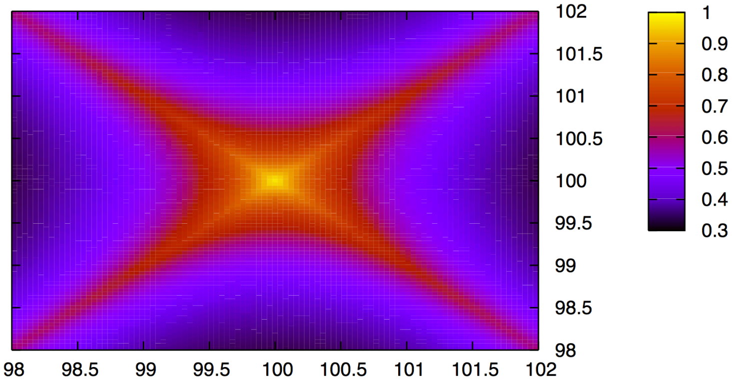
The simplest search strategy:

1. Choose randomly one dimension (x_i)
2. Choose one direction (increase or decrease)
3. Make a step Δ
4. If the fitness increases, move to the new point
5. If the fitness decreases, stay in the same point

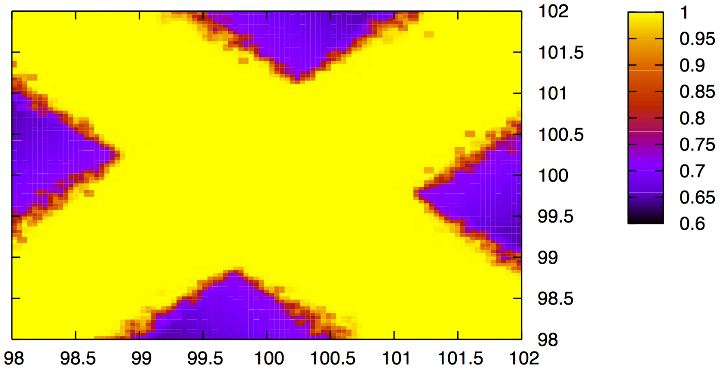
Landscape $a_{i,j} = 0$



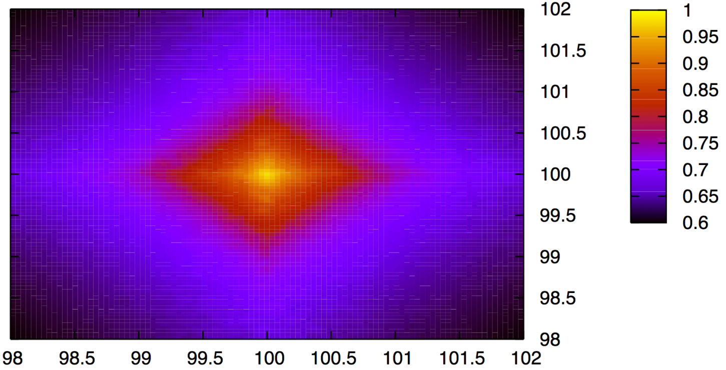
Landscape $a_{i,j} = 1$



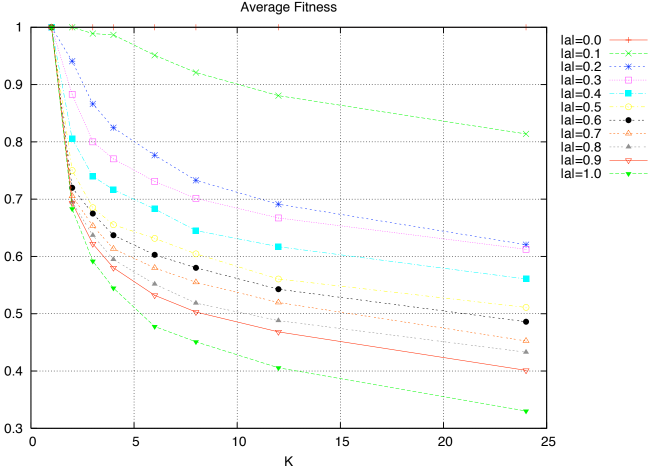
Final fit. with one-dimensional search; $a_{i,j} = 0.25$



Final fit. with one-dimensional search; $a_{i,j} = 1.00$

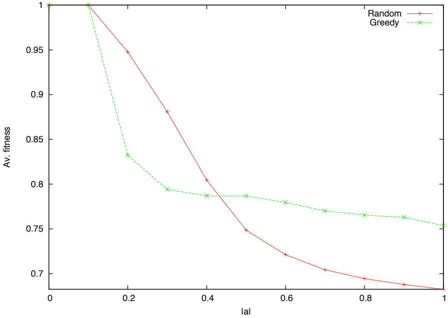


Number of dimensions



Random vs. Greedy strategy

Greedy: Check all four possible directions and move towards the one with the largest fitness increase



High a_{ij}: move towards the highest local optimum
Low a_{ij}: premature convergence

Lock-in

Brian Arthur's model on technology choice and dominance

Externalities and increasing returns

The adoption of a technology influences later adopters

- Economies of scale
- Learning, accumulation of knowledge and experiences
- Technological interrelatedness
- Network externalities
- Imitation
- Infrastructures

Adopters value a technology for its value and for the value added by wider use

Brian Arthur's model

Agent R prefers technology A
Agent S prefers technology B

$$\text{Utility } R = \begin{cases} a_R + rN_A & \text{if she adopts } A \\ b_R + rN_B & \text{if she adopts } B \end{cases}$$

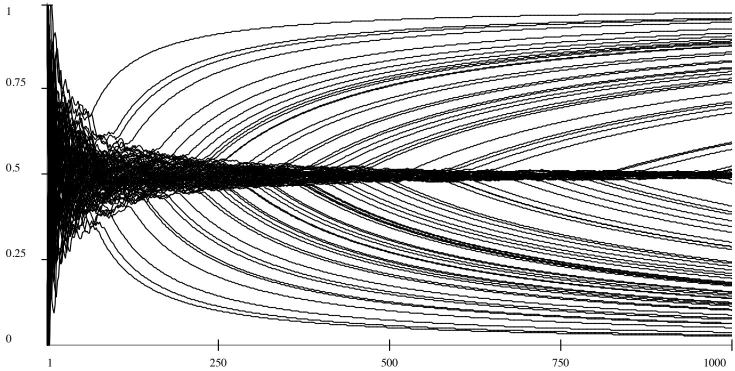
$$\text{Utility } S = \begin{cases} a_S + sN_A & \text{if she adopts } A \\ b_S + sN_B & \text{if she adopts } B \end{cases}$$

where $a_R > b_R$; $a_S < b_S$; N_A and N_B are number of adopters of A and B; r and s network externalities for R and S

An agent of type R or S is randomly drawn to choose the technology

Brian Arthur's model

Market shares through time with $r = s = 0.2$



Directions and path dependence

Simply a sequence of randomly drawn consumers determine long term choice of one technology

$\Rightarrow$ says little about the actual superiority of a technology

A number of factors determine the choice of a technology, and the future development of humanity: e.g. green technologies

Simulation model of the Risk-Reward Nexus

Risk-Reward Nexus (RRN): A framework of analysis

- Contribution to the innovation process relative to the financial rewards reaped from it (Mazzucato, 2013; Lazonick and Mazzucato, 2013)

  Difficult to establish *a priori* a tight connection between the bearing of risk and the ensuing returns

Evolutionary model of the RRN:

- Simulation model of technological competition and product diffusion in an industry producing a final product of varying quality, determined by the degree of development of a new technology required as input
- 2 agent-types

  ATypeA: public sector ATypeB: private firms, indexed with $i = 1, \ldots, n_B(t)$
- Understand the mechanisms underlying the (relative) imbalance between risks and rewards
- and the role of the Public Sector in their realignment

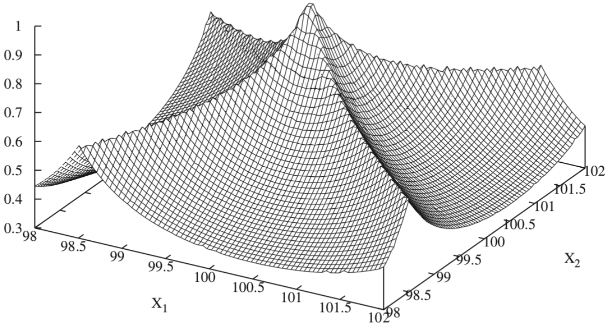
The model in a nutshell

"The public sector directly invests in R&D, either at an early stage or throughout the innovation chain, charging a license cost to firms in order to access accumulated technological knowledge. Private firms may take advantage of the privileged landscape position reached by the public sector, acquiring the license to operate the new technology and obtaining a relatively high fitness score in the technology landscape, product quality and market share, thus accessing innovation rents. Profits made by firms are channelled as dividends, whereas investment in R&D contributes to the development of skills of R&D workers, increasing wages."

Technological competition: fitness landscape

Technology is represented by the fitness landscape of a pseudo-NK model (Valente, 2014):

- N-dimensional multi-peaked surface (with a unique *global* peak)
- K-interactions among dimensions: fitness-increasing movements in one direction contingent on the position in other dimensions
- Each agent's landscape position maps into a *fitness* score ($\alpha^i(t)$) that measures distance to *dominant design*, determining product quality



Technology, innovation, quality and demand

Average contribution to fitness in an industry of $n_B(t)$ firms and a public sector:

$$\overline{\alpha}(t) = \frac{1}{n_B(t)+1}\left(\sum_{i=1}^{n_B(t)} \alpha^i(t) + \alpha^A(t)\right) \tag{3}$$

Exploration strategy: series of one-bit mutations increasing in R&D investment

$$\lambda^i(t) = \psi(RD^i(t)), \qquad \frac{d\psi}{dRD^i(t)} > 0 \tag{4}$$

Total final demand (i.e. size of the market) related to average product quality by a logistic curve (Figure):

$$F(t) = \frac{100}{1 + e^{-\phi_1(\phi_2\overline{\alpha}(t)-\phi_3)}} \tag{5}$$

Firm dynamics

Final demand of firm i as a share $\theta^i(t)$ in total final demand $F(t)$:

$$f^i(t) = \theta^i(t) F(t), \quad \text{such that} \quad \sum_{i=1}^{n_B(t)} f^i(t) = F(t) \tag{6}$$

Link between technological competition and market competition: (tamed) replicator equation (Metcalfe, 1994)

$$\theta^i(t) = \theta^i(t-1) \left(1 + \chi \frac{\alpha^i(t) - \overline{\alpha}^B(t-1)}{\overline{\alpha}^B(t-1)} \right) \tag{7}$$

where χ is the intensity of replicator dynamics.

Firm dynamics, market shares, value creation/extraction

Value created within each firm i, realised in profits by selling the final product:

$$\pi^i(t) = (1-\tau)f^i(t) - RD^i(t) - c_A^i(t) \tag{8}$$

where $\tau f^i(t)$ are taxes on revenues; $c_A^i(t)$ is the payment to the public sector of a license to access the new technology.

Role of market competition in innovation development:

$$RD^i(t) = \begin{cases} \underline{\eta}(1-\tau)f^i(t-1), & \text{if } \theta^{(i)}(t) < 1/2 \text{ and } F(t) > 50 \\ \overline{\eta}(1-\tau)f^i(t-1), & \text{otherwise} \end{cases} \tag{9}$$

where $(\underline{\eta}, \overline{\eta})$, with $\underline{\eta} < \overline{\eta}$ indicate alternative propensities to spend in R&D out of (net-of-taxes) sales

Entrants rip ϵ market share of the biggest incumbent, and incumbents exit when their market share is below threshold $\underline{\theta}$

The public sector, licenses and inequality

Government income $Y^A(t)$:

$$Y^A(t) = \sum_{i=1}^{n_B(t)} \tau f^i(t) + \sum_{i=1}^{n_B^{Lic}(t)} c_A^i(t) - RD^A(t) \tag{10}$$

Household income is composed of wages $W(t)$ and dividends $Div(t)$:

$$Y^H(t) = W(t) + Div(t), \quad \Omega_W(t) = \frac{W(t)}{Y^H(t)} \tag{11}$$

R&D is addressed to wages, profits channelled to dividends:

$$W(t) = RD^A(t) + \sum_{i=1}^{n_B(t)} RD^i(t), \quad Div(t) = \sum_{i=1}^{n_B(t)} \pi^i(t) \tag{12}$$

Household income and government income exhaust total final demand

Relative risks and rewards: the Risk-Reward Nexus

Risk $\sigma^i(T^i)$ and reward $\mu^i(T^i)$ for private firm i:

$$\sigma^i(T^i) = (1-\alpha^i(0))(\alpha^i(T^i)-\alpha^i(0)), \quad \mu^i(T^i) = \frac{1}{T^i}\sum_{t=0}^{T^i}\pi^i(t)$$

where T^i is the period of firm i exit.

Risk $\sigma^A(T)$ and reward $\mu^A(T)$ for the public sector:

$$\sigma^A(T) = (1-\alpha^A(0))(\alpha^A(T)-\alpha^A(0)), \quad \mu^A(T) = \frac{1}{T}\sum_{t=0}^{T}Y^A(t)$$

Risk-Reward Nexus:

$$RRN^i(T^i) = \frac{\mu^i(T^i)}{\sigma^i(T^i)}, \qquad RRN^A(T) = \frac{\mu^A(T)}{\sigma^A(T)}$$

Alternative scenarios: Specification

Table: Simulation scenarios

Competition ($\underline{\theta}, \chi, \epsilon$)	Tech-Complexity (a_{ij})	Public R&D	Scenario	Competition $\underline{\theta}$	χ	ϵ	Tech-Cpx a_{ij}
Stringent	Medium	Throughout	1	0.04	0.50	0.20	0.35
		Early stage	2				
	High	Throughout	3	0.04	0.50	0.20	0.60
		Early stage	4				
Lax	Medium	Throughout	5	0.04	0.25	0.10	0.35
		Early stage	6				

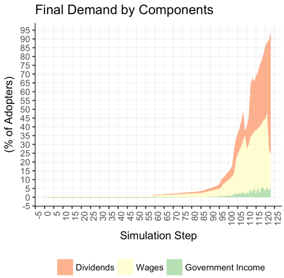
References: $\underline{\theta}$: Minimum market share;
χ: Intensity of replicator dynamics;
ϵ: Proportion of market share reaped by entrants;
a_{ij}: Intensity of interaction across dimensions of the pseudo-NK landscape

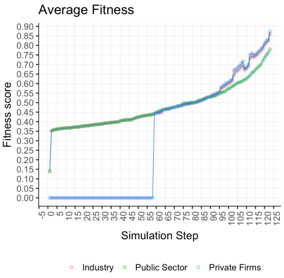
Across-scenario parameters

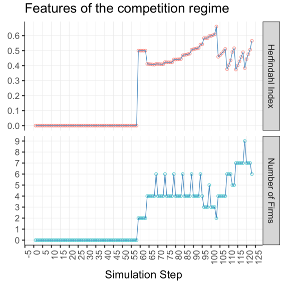
Param.	Description	Range	Value
	Complexity of the technology: pseudo-NK landscape		
N	Landscape dimensions	≥ 2	2
K	Interactions among dimensions	≥ 1	1
	Competition regime		
$\underline{\theta}$	Minimum market share	$[0, 1]$	0.04
	Public policy		
τ	Tax rate on sales	$[0, 1]$	0.10
ξ	License fee rate to access the new technology	$[0, 1]$	0.03
ι^*	Target proportion of public R&D stock	$[0, 1]$	0.17
	R&D investment		
δ	R&D depreciation rate	$[0, 1]$	0.02
$\underline{\eta}$	Propensity to invest in R&D out of sales (Low)	$[0, 1]$	0.40
$\underline{\eta}$	Propensity to invest in R&D out of sales (High)	$[0, 1]$	0.70

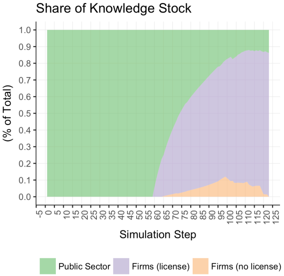
Simulation steps = 150; entrants per entry-period = 2; entry interval = 4.

Baseline scenario simulation run: Plots









Baseline scenario simulation run: Numerical details

Table: Risks, Rewards, Share in Accumulated Profits and Knowledge Stock

(Baseline results, scenario **1**: throughout-publicRD, medium-tech, stringent-competition)

Agent	Entry Time	Exit Time	Pays License	Risk	Reward	RRN	Profits Share	Knowledge Stock
				(t-average accum. in T)				
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
1	1	150		0.551	0.427	0.774	0.00	66.05
2	59	103	Yes	0.053	0.181	3.439	1.23	0.00
3	59	150	Yes	0.312	7.844	25.134	79.28	291.94
4	64	123	No	0.090	0.757	8.402	6.93	0.00
5	64	96	Yes	0.027	0.050	1.877	0.25	0.00
20	104	120	No	0.023	0.884	38.014	2.09	0.00
21	104	150	Yes	0.064	1.299	20.188	3.90	43.77
22	109	150	Yes	0.050	1.068	21.445	2.36	28.04
23	109	112	No	0.004	0.278	69.054	0.09	0.00
24	114	119	No	0.016	0.736	45.204	0.46	0.00
25	114	150	Yes	0.023	1.270	56.218	1.80	24.15
26	119	150	Yes	0.015	1.220	83.455	0.77	12.45
27	119	150	Yes	0.016	1.312	82.545	0.83	12.78
Average Private Firms				0.259	6.415	25.257		
Relative Risks and Rewards				0.470	15.023	32.631		

Specifications: Simulation steps = 150; entrants per entry-period = 2; entry interval = 4. Failure Rate = 0.538. Notes: Time period T: simulation step in which the dominant design has been reached by one of the private firms; columns [6]-[8]: time-averages of values accumulated up to period T.

Simulation results: alternative scenarios

Table 1: Simulation results: alternative scenarios

(across-run averages over 50 replications for each scenario, p-values correspond to Welch's unequal variances t-test comparing scenarios 1 with 2, 3 with 4, 5 with 6, respectively)

	Indicator	Scenario 1	Scenario 2	Difference p-value	Scenario 3	Scenario 4	Difference p-value	Scenario 5	Scenario 6	Difference p-value
Final Demand	1.1 Average Final Demand	20.586	23.003	0.0022	21.255	18.994	0.0000	20.696	27.859	0.0000
	1.2 Final Demand at T	83.541	80.628	0.4714	33.270	28.333	0.0000	87.185	90.022	0.4677
	1.3 Accumulated Final Demand	1420.605	1423.973	0.9703	2859.232	2563.385	0.0000	1401.397	1635.089	0.0055
Inequality	Shares in Accumulated Final Demand									
	2.1 Government Income	0.032	0.085	0.0000	0.048	0.098	0.0000	0.030	0.088	0.0000
	2.2 Wages	0.557	0.447	0.0000	0.676	0.623	0.0000	0.509	0.446	0.0000
	2.3 Dividends	0.401	0.457	0.0002	0.273	0.275	0.0002	0.456	0.464	0.5401
	2.4 Wage share in Household Income	0.577	0.490	0.0000	0.711	0.691	0.0000	0.526	0.490	0.0105
	Share in Accumulated Profits									
	2.5 Private Firms (license)	0.832	0.000	0.0000	0.714	0.000	0.0000	0.641	0.000	0.0000
	2.6 Private Firms (no license)	0.168	1.000	0.0000	0.286	1.000	0.0000	0.359	1.000	0.0000
Market Concentration	Herfindahl Market Concentration Index									
	3.1 Average across time periods	0.482	0.562	0.0002	0.366	0.436	0.0001	0.592	0.568	0.0433
	3.2 At time T	0.547	0.777	0.0000	0.246	0.273	0.2052	0.679	0.719	0.1688
Knowledge Accumulation	Shares in Knowledge Stock									
	4.1 Public	0.159	0.012	0.0000	0.311	0.046	0.0000	0.170	0.015	0.0000
	4.2 Private Firms (license)	0.750	0.000	0.0000	0.547	0.000	0.0000	0.590	0.000	0.0000
	4.3 Private Firms (no license)	0.090	0.988	0.0000	0.143	0.954	0.0000	0.240	0.985	0.0000
Rewards	5.1 Private Firms	5.215	8.582	0.0000	1.578	1.739	0.0892	6.928	9.572	0.0000
	5.2 Public Sector	0.390	1.066	0.0000	0.910	1.667	0.0000	0.379	1.281	0.0000
	5.3 Relative Rewards (Private/Public)	16.925	8.640	0.0000	1.751	1.048	0.0000	18.926	7.727	0.0000
Risks	6.1 Private Firms	0.200	0.250	0.0008	0.062	0.059	0.3923	0.244	0.259	0.2405
	6.2 Public Sector	0.465	0.236	0.0000	0.341	0.214	0.0000	0.481	0.225	0.0000
	6.3 Relative Risk (Private/Public)	0.447	1.100	0.0000	0.197	0.329	0.0000	0.533	1.214	0.0000
Risk-Reward Nexus	7.1 Private Firms	42.139	38.370	0.6370	54.438	88.356	0.0728	31.008	36.586	0.0067
	7.2 Public Sector	0.848	4.768	0.0000	2.852	9.482	0.0000	0.807	6.004	0.0000
	7.3 Relative Risk-Reward (Private/Public)	47.033	8.509	0.0000	20.243	11.160	0.0108	33.847	6.645	0.0007

References for scenarios:
1. throughout-publicRD, medium-tech, stringent-competition; **2**. early-publicRD; medium-tech, stringent-competition;
3. throughout-publicRD, high-tech, stringent-competition; **4**. early-publicRD; high-tech, stringent-competition;
5. throughout-publicRD, medium-tech, lax-competition; **6**. early-publicRD; medium-tech, lax-competition.

Simulation results: Risk-Reward Nexus

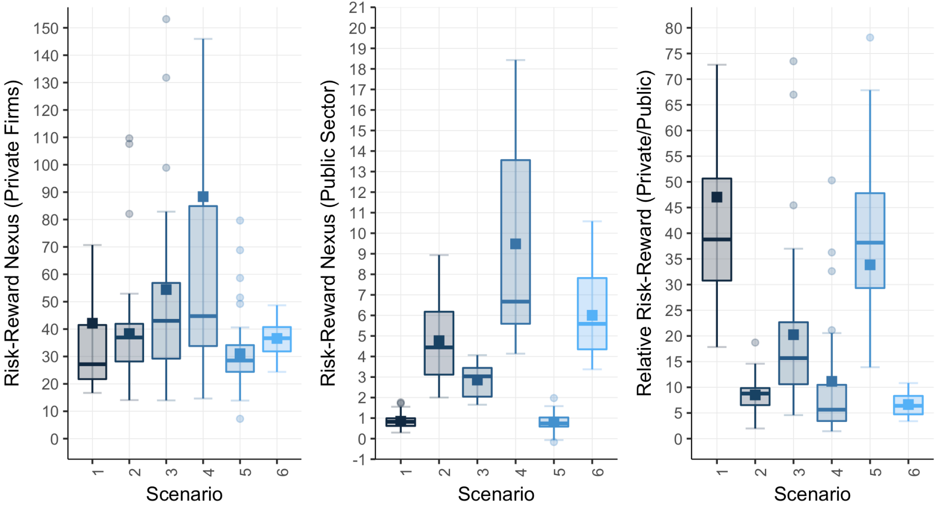


Figure: Private, Public and Relative Risk-Reward Nexus

(Bar: median, square: mean, rectangular box: 2nd-3rd quartile, whiskers: max-min, dots: outliers)

Policy scenarios

Table: Simulation scenarios: Adaptive vs. Static policy

Competition	Tech-Complexity	Public R&D	Policy	Scenario
Stringent	Medium	Throughout	Adaptive	7
		Early stage	Static	2
	High	Throughout	Adaptive	8
		Early stage	Static	4
Lax	Medium	Throughout	Adaptive	9
		Early stage	Static	6

Adaptive policy:

$$\tau(t) = \begin{cases} \tau(t-1) + 0.01, & \text{if } RRN^A(t-1) < RRN^{A,*}(t-1) \\ \tau(t-1) - 0.01, & \text{if } RRN^A(t-1) > RRN^{A,*}(t-1) \end{cases} \quad (13)$$

$$\xi(t) = \begin{cases} \xi(t-1) + 0.01, & \text{if } RRN^A(t-1) < RRN^{A,*}(t-1) \\ \xi(t-1) - 0.01, & \text{if } RRN^A(t-1) > RRN^{A,*}(t-1) \end{cases} \quad (14)$$

where $\tau = 0.1$ and $\xi = 0.03$ set a lower bound to the downward adjustments.

Simulation results: policy scenarios

Table 2: Simulation results: adaptive policy under alternative scenarios

(across-run averages over 50 replications for each scenario, p-values correspond to Welch's unequal variances t-test comparing scenarios 7 with 2, 8 with 4, 9 with 6, respectively)

	Indicator	Scenario 7	Scenario 2	Difference p-value	Scenario 8	Scenario 4	Difference p-value	Scenario 9	Scenario 6	Difference p-value
Rewards	5.1 Private Firms	4.440	9.062	0.001	1.257	1.696	0.014	5.748	10.181	0.057
	5.2 Public Sector	2.461	1.026	0.000	3.001	1.632	0.000	2.607	1.296	0.000
	5.3 Relative Rewards	2.304	9.040	0.000	0.433	1.050	0.000	2.353	8.187	0.000
Risks	6.1 Private Firms	0.198	0.263	0.112	0.050	0.059	0.372	0.239	0.257	0.775
	6.2 Public Sector	0.582	0.235	0.000	0.383	0.215	0.000	0.608	0.225	0.000
	6.3 Relative Risk	0.347	1.152	0.000	0.145	0.329	0.000	0.400	1.202	0.000
Risk-Reward Nexus	7.1 Private Firms	35.425	35.602	0.427	77.606	100.635	0.374	28.888	41.878	0.367
	7.2 Public Sector	4.273	4.509	0.000	7.976	9.078	0.000	4.312	5.987	0.000
	7.3 Relative Risk-Reward	8.365	8.153	0.001	9.227	13.888	0.107	6.700	7.325	0.128
Policy instruments	8.1 License Fee Rate	0.188	0.030		0.209	0.030		0.203	0.030	
	8.2 Tax Rate on Revenues	0.269	0.100		0.296	0.100		0.286	0.100	

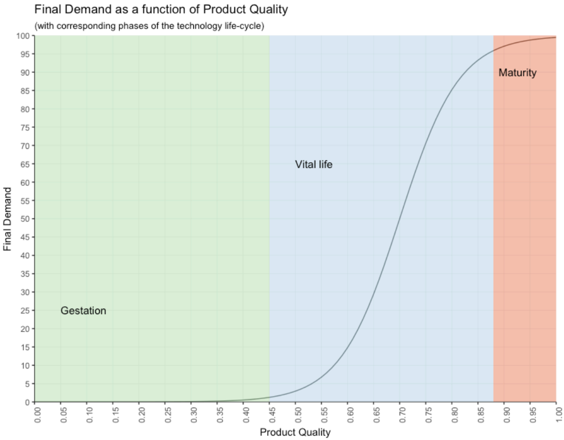
References for scenarios:

7. throughout-publicRD, medium-tech, stringent-competition, adaptive policy; **2**. early-publicRD; medium-tech, stringent-competition, static policy;
8. throughout-publicRD, high-tech, stringent-competition, adaptive policy; **4**. early-publicRD; high-tech, stringent-competition, static policy;
9. throughout-publicRD, medium-tech, lax-competition, adaptive policy; **6**. early-publicRD; medium-tech, lax-competition, static policy.

Final remarks

- Relative risk-reward nexus (rewards/risks) increases in favour of private firms whenever the public sector directly invests in R&D throughout the innovation chain, and this increase is sharper the lower the complexity of the new technology;
- Workers are the ultimate source of skills and innovation development: increasing the wage share with R&D investment, the public sector drives the process of landscape exploration and reduces the extent of value extraction through dividends;
- When the technology is complex, a stringent competition regime cannot replace the direct action of the public sector investing in R&D;
- An adaptive rule for taxation and licensing suggests that the public sector can, in principle, realign the Risk-Reward Nexus between 'early R&D only' and 'R&D throughout' investment scenarios. And make innovation sustainable.

Demand (Back)


Final Demand as a function of Product Quality
(with corresponding phases of the technology life-cycle)
Final Demand
Product Quality
Gestation
Vital life
Maturity
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00

References I

Aversi, R., Dosi, G., Fagiolo, G., Meacci, M., and Olivetti, C. (1999). Demand Dynamics with Socially Evolving Preferences. *Industrial and Corporate Change*, 8(2):353–408.

Kahneman, D. and Tversky, A., editors (2000). *Choices, Values, and Frames [Paperback]*. Cambridge University Press.

Kauffman, S. A. and Levin, S. (1987). Towards a general theory of adaptive walks on rugged landscapes. *Journal of Theoretical Biology*, 128(1):11–45.

Lazonick, W. and Mazzucato, M. (2013). The risk-reward nexus in the innovation-inequality relationship: who takes the risks? Who gets the rewards? *Industrial and Corporate Change*, 22(4):1093–1128.

Mazzucato, M. (2013). *The Entrepreneurial State: Debunking Public Vs. Private Sector Myths*. Anthem Press.

References II

Metcalfe, J. S. (1994). Competition, Fisher's Principle and increasing returns in the selection process. *Journal of Evolutionary Economics*, 4(4):327–346.

Metcalfe, J. S. (2014). Capitalism and evolution. *Journal of Evolutionary Economics*, 24(1):11–34.

Saviotti, P. P. and Metcalfe, J. S. (1984). A Theoretical Approach to the Construction of Technological Output Indicators. *Research Policy*, 13:115–141.

Sen, A. (1980). Plural Utility. *Proceedings of the Aristotelian Society*, 81:193–215.

Simon, H. A. (2002). Near decomposability and the speed of evolution. *Industrial and Corporate Change*, 11(3):587–599.

References III

Valente, M. (2012). Evolutionary demand: a model for boundedly rational consumers. *Journal of Evolutionary Economics*, 22(5):1029–1080.

Valente, M. (2014). An NK-like model for complexity. *Journal of Evolutionary Economics*, 24(1):107–134.

Witt, U. (2001). Learning to Consume - A Theory of Wants and the Growth of Demand. *Journal of Evolutionary Economics*, 11:23–36.