Complexity and Emergence: Ideas, Methods, with a special attention to Economics and Finance

Summer School

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AFD & Chair Energy and Prosperity

Outlines

Economics

Economics *stricto sensu* deal with production, exchange and consumption of goods;

Economics (and economists) split between micro- and macro-

- Microeconomics deal with individual behaviour
- Macroeconomics deal with aggregate behaviour (nations)

Which comes first?

- The Hegelian tradition (Marx and the superstructures)
- The liberal tradition (Smith and the invisible hand)

Macroeconomics: the variables

Macroeconomics deals with aggregate variables describing the state of a population:

- GDP
- unemployment rate
- growth rate
- cost of living
- purchasing power
- poverty line
- inequality
- life expectancy
- balance of payments

Was there a crisis in 2008 ?

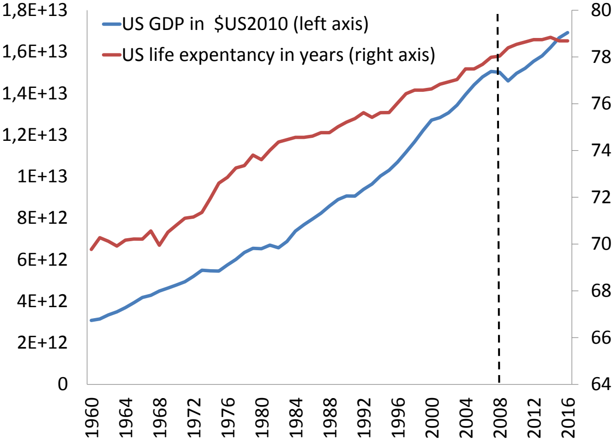
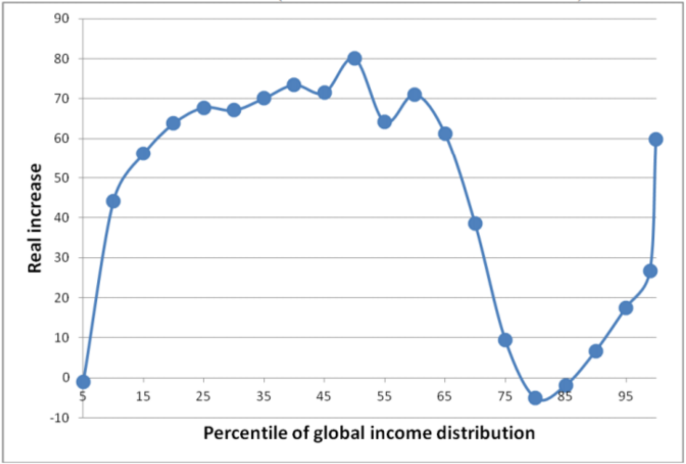


Figure: TBD

Milankovic's elephant curve

Figure 4. Change in real income between 1988 and 2008 at various percentiles of global income distribution (calculated in 2005 international dollars)



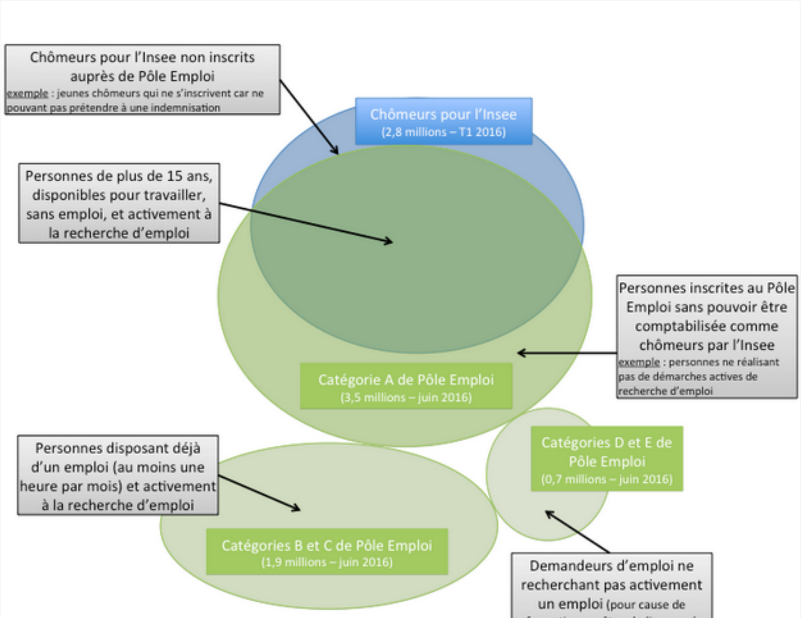
Note: The vertical axis shows the percentage change in real income, measured in constant international dollars. The horizontal axis shows the percentile position in the global income distribution. The percentile positions run from 5 to 95, in increments of five, while the top 5% are divided into two groups: the top 1%, and those between 95th and 99th percentiles.

Constructing the macroeconomic variables

The macroeconomic variables cannot be measured directly. They are constructed to encompass in a single number a multidimensional reality:

- the GDP: counts only what is priced by the market. NOT the depletion of natural resources , NOT unpaid work (women at home, subsistence farming). The financial sector contributes 0.065 of GDP In GB, 0.27 in Luxembourg
- cost of living: how does one compare 1990 prices (no internet, no laptops, no smartphones) with 2018 prices ? Does the price of cars increase or decrease? Does the price of housing increase or decrease? Can one build an index for this?
- inequality: who earns what ? who owns what ? How much is it worth ? The missing money (Zucman).

Defining the unemployment rate



Are there macroeconomics laws ?

- There is no logical reason why there should exist relations between macroeconomic variables
- This has been said several times during this conference:
  - Coleman's boat
  - Entropy hierarchies

Are there macroeconomic regularities ?

Some candidates

- If prices increase, consumption decreases. This is the so-called law of demand, which has been studied by Werner Hildenbrand. He concludes it cannot be verified directly, so he verifies proxies (dispersion of wealth in the population)
- The business cycle:
  - the European view: boom-and-bust is inherent to capitalism
  - the Chicago view: the problem has been solved

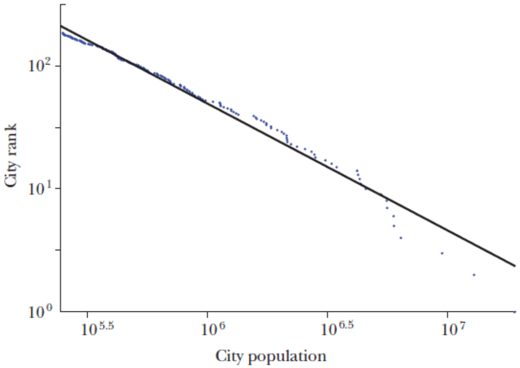
Macroeconomics was born as a distinct field in the 1940s, as a part of the intellectual response to the Great Depression. The term then referred to the body of knowledge and expertise that we hoped would prevent the recurrence of that economic disaster. My thesis in this lecture is that macroeconomics in this original sense has succeeded: its central proble, of depression prevention has been solved, for all practical purposes, and has in fact been solved for decades (Bob Lucas, 2003)

Another candidate: Zipf's law

Gabaix, 2016

Figure 1

A Plot of City Rank versus Size for all US Cities with Population over 250,000 in 2010

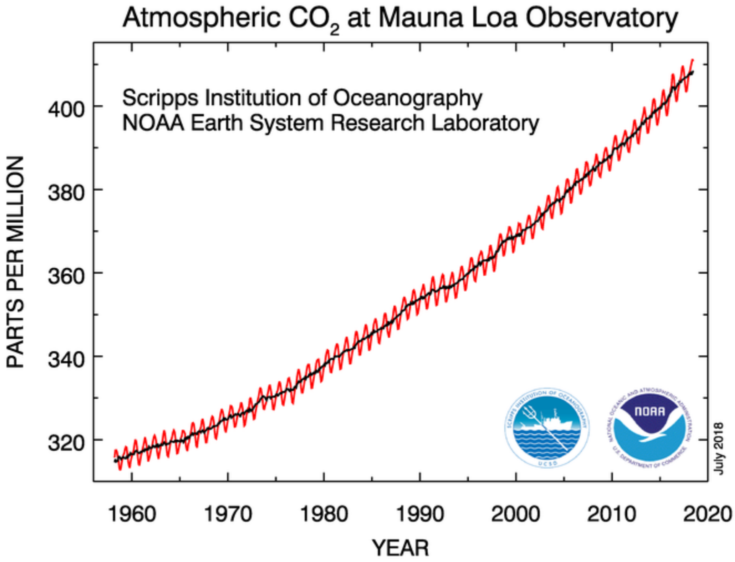


Source: Author, using data from the *Statistical Abstract of the United States* (2012).
Notes: The dots plot the empirical data. The line is a power law fit ($R^2 = 0.98$), regressing ln *Rank* on ln *Size*. The slope is -1.03, close to the ideal Zipf's law, which would have a slope of -1.

No one saw it coming

- The world until 1973: planning and macromodels
- The oil crisis of 1973: no one saw it coming. Why ?
  - Macroeconomics is not a closed system
  - The effect of important individuals
- The end of the macromodels: the Lucas critique
  - In economics, the state tomorrow depends on current state and expectations
  - If predictions are made at all, the economic actors are aware of them and will adjust their behaviour accordingly
  - So predictions should not be made at all, or should be self-fulfilling
- The 2008 financial crisis: no one saw it coming
  - This time, it's different
  - The role of money
  - The role of institutions and rules
  - There is no law of economics independent of the planet (resources, biodiversity), culture and politics, money and microregulation

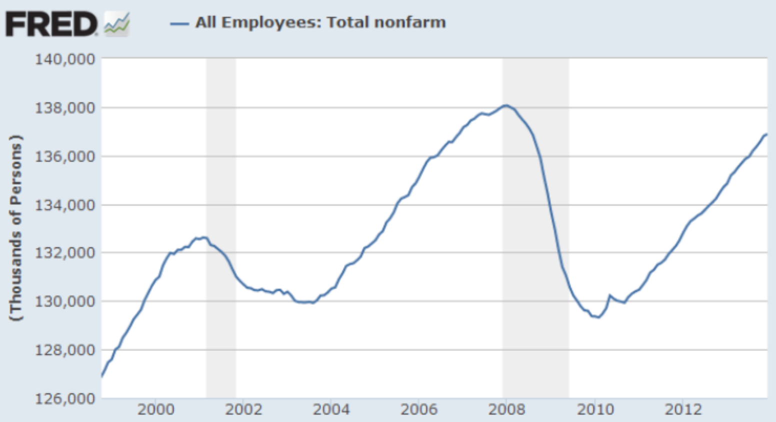
The ultimate crisis



Outlines

Originates in the financial sector and morphs into an economic crisis

Impact on jobs



A long lasting crisis

Unemployment shot up, and broadly defined is still very high

The state of macroeconomics

The macroeconomic fundamentals on the real side were good

- Technology continues to progress (iPhone in 2007, iPad in 2010, fracking and solar made big advances)

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- Capital stock is growing, even if not as fast

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- Capital stock is growing, even if not as fast
- So, productive capacity of the economy has surely risen a lot
- But actual production drops sharply, then sluggish recovery

A feeling of déjà vu

A feeling of déjà vu

This is a nightmare, which will pass away with the morning. For the resources of nature and men's devices are just as fertile and productive as they were. The rate of our progress towards solving the material problems of life is not less rapid. We are as capable as before of affording for everyone a high standard of life—high, I mean, compared with, say, twenty years ago—and will soon learn to afford a standard higher still. We were not previously deceived. But to-day we have involved ourselves in a colossal muddle, having blundered in the control of a delicate machine, the working of which we do not understand. The result is that our possibilities of wealth may run to waste for a time—perhaps for a long time.

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(Keynes, "The Great slump of 1930")

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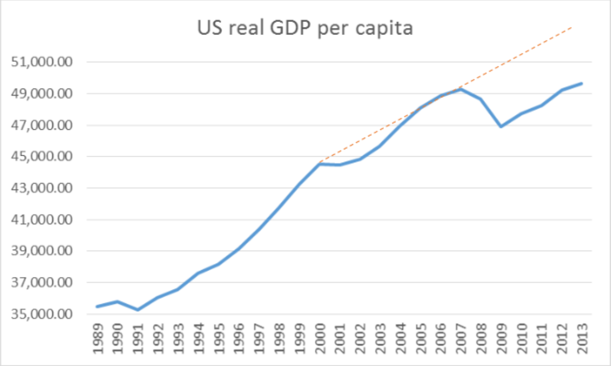
(Keynes, "The Great slump of 1930") But how did we manage to do it again?

The 2008 financial crisis

The Great Recession was a huge setback. How could this happen?



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The 2008 financial crisis

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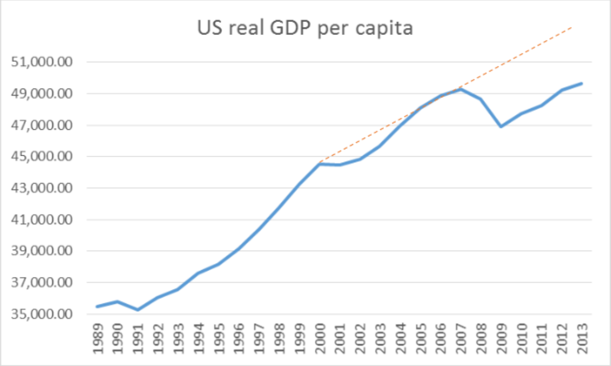
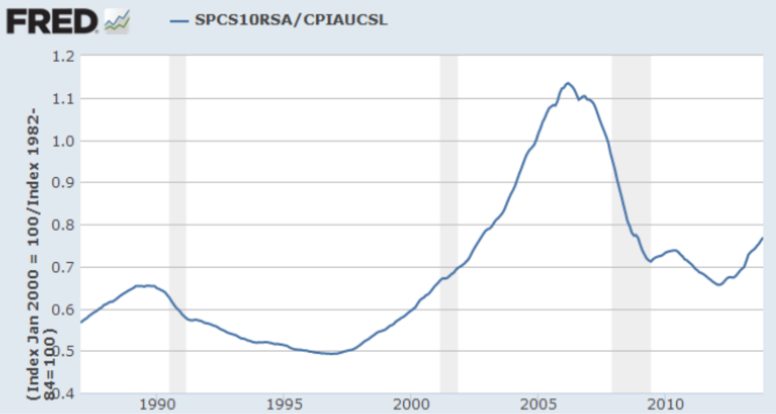


Again, the economic fundamentals were good –To understand how this could happen, we shall focus on the monetary economics: money is not neutral.

The 2008 financial crisis

What happened?

What do we know about the causes? A huge bubble in housing prices



The 2008 financial crisis

What happened?

Large rise in household debt as ratio to GDP–increasing leverage

The 2008 financial crisis

Money creation

The 2008 financial crisis

Money creation

Two misconceptions about money creation:

The 2008 financial crisis

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- Banks act simply as intermediaries, lending out the deposits that savers place with them

The 2008 financial crisis

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Lending creates deposits

The 2008 financial crisis
Money creation

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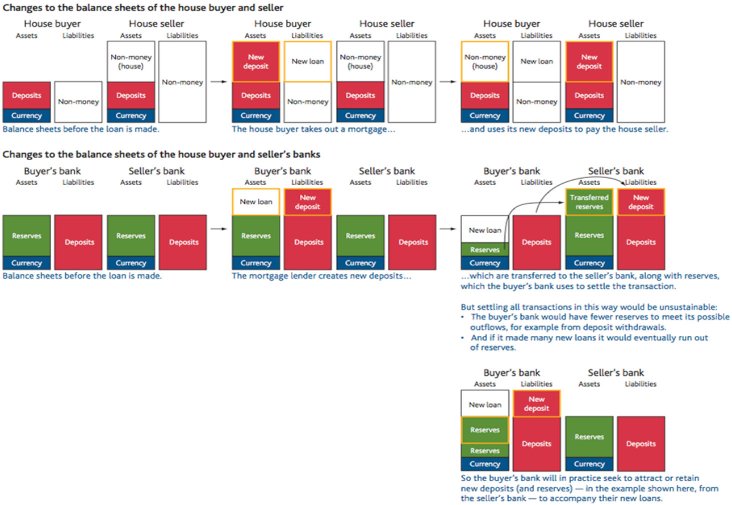
Lending creates deposits

Example: let's a assume a household decides to buy a house from another household, using a 100% LTV mortgage.

The 2008 financial crisis

Whole story of money creation

Figure 2 Money creation for an individual bank making an additional loan[(a)]



The 2008 financial crisis

Limits to money creation

Can banks create money *ad libitum*?

- Banks' limits
  - Profitability
  - Risks
  - Regulatory Policy

The 2008 financial crisis

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  - Hot potato

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The 2008 financial crisis

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Note that: The rules are man-made

The 2008 financial crisis

Money and finance misrepresentation: implication

Failing to understand the endogenous nature of bank money leads to **underestimate the sources of financial instability** and the consequences of shocks hitting the banking sector.

The 2008 financial crisis

Nobody saw it coming?

- How did the bubble start? (Low interest rate, saving glut, great moderation)

The 2008 financial crisis

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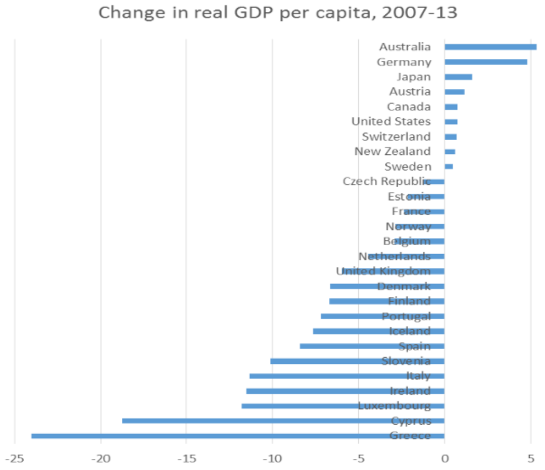
- How did the bubble start? (Low interest rate, saving glut, great moderation)
- The burst of the housing bubble and its consequences. (lower demand, increase interest rate: bankruptcy of Lehman Brothers)

The 2008 financial crisis

Nobody saw it coming?

- How did the bubble start? (Low interest rate, saving glut, great moderation)
- The burst of the housing bubble and its consequences. (lower demand, increase interest rate: bankruptcy of Lehman Brothers)
- How a housing crisis became a financial crisis? (complex financial instruments–MBS, CDO, CDS–, lack of regulation, shadow banking, rating agencies, led to cascade effects at the world scale)

A worldwide contagion



Nobody saw it coming? Not true...

Someone anticipated the crisis with remarkable precision regarding the timing and the mechanism of the collapse using a flow-of-funds approach (Godley, 1999, Godley and Wray, 1999, Godley and Zezza, 2006).

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Which methodology did they use? The so-called “flow of funds”, or “accounting”, “balance sheet” approach is at the base of Stock Flow Consistent (SFC) models, whose fundamental features were defined in Godley and Lavoie (2007).

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This approach allowed them to follow the money and to keep track of the debts.

The 2008 financial crisis

SFC models: Accounting logic

- Someone's asset is someone else liability AND someone inflow is someone else outflow
  - *quadruple entry system* (Copeland, 1949)–follow the money

The 2008 financial crisis

SFC models: Accounting logic

- Someone's asset is someone else liability AND someone inflow is someone else outflow
  - *quadruple entry system* (Copeland, 1949)–follow the money
- Budget constraint for each individual sector and for the economy as a whole
  - "Walras' law and adding up constraint" (Tobin, 1982)
  - "budget constraint or system-wide consistency requirement", Godley and Lavoie (Godley, 2007)

The 2008 financial crisis

Quadruple entry - Government expenditures financed by central bank

	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.						
Income (GDP)						
ΔCash						
ΔDep						
ΔBills						
sum						

The 2008 financial crisis

Quadruple entry - Government expenditures financed by central bank

	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.						
Income (GDP)						
ΔCash						
ΔDep						
ΔBills				-ΔB		
sum						

The 2008 financial crisis

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	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.						
Income (GDP)						
ΔCash						
ΔDep						
ΔBills				$-\Delta B$	$+\Delta B_{cb}$	
sum						

The 2008 financial crisis

Quadruple entry - Government expenditures financed by central bank

	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.						
Income (GDP)						
ΔCash					-ΔH	
ΔDep						
ΔBills				-ΔB	+ΔB_{cb}	
sum						

The 2008 financial crisis

Quadruple entry - Government expenditures financed by central bank

	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.						
Income (GDP)						
ΔCash				$+\Delta H_g$	$-\Delta H$	
ΔDep						
ΔBills				$-\Delta B$	$+\Delta B_{cb}$	
sum						

The 2008 financial crisis

Quadruple entry - Government expenditures financed by central bank

	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.						
Income (GDP)						
ΔCash				$+\Delta H_g$	$-\Delta H$	0
ΔDep						
ΔBills				$-\Delta B$	$+\Delta B_{cb}$	0
sum				0	0	0

The 2008 financial crisis

Quadruple entry - Government expenditures financed by central bank

	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.				+G		
Income (GDP)						
ΔCash					-ΔH	
ΔDep						
ΔBills				-ΔB	+ΔB_{cb}	
sum						

The 2008 financial crisis

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Gov. Exp.		-G		+G		
Income (GDP)						
ΔCash					-ΔH	
ΔDep						
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sum						

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	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.		-G		+G		
Income (GDP)						
ΔCash					-ΔH	
ΔDep		+ΔM_f				
ΔBills				-ΔB	+ΔB_{cb}	
sum						

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	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.		-G		+G		
Income (GDP)						
ΔCash					-ΔH	
ΔDep		+ΔM_f	-ΔM			
ΔBills				-ΔB	+ΔB_{cb}	
sum						

The 2008 financial crisis

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	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.		-G		+G		
Income (GDP)						
ΔCash			$+\Delta H_b$		$-\Delta H$	
ΔDep		$+\Delta M_f$	$-\Delta M$			
ΔBills				$-\Delta B$	$+\Delta B_{cb}$	
sum						

The 2008 financial crisis

Quadruple entry - Government expenditures financed by central bank

	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.		-G		+G		0
Income (GDP)						
ΔCash			$+\Delta H_b$		$-\Delta H$	0
ΔDep		$+\Delta M_f$	$-\Delta M$			0
ΔBills				$-\Delta B$	$+\Delta B_{cb}$	0
sum		0	0	0	0	0

The 2008 financial crisis

Quadruple entry - Government expenditures financed by central bank

	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.		-G		+G		
Income (GDP)		+Y				
ΔCash					-ΔH	
ΔDep						
ΔBills				-ΔB	+ΔB_{cb}	
sum						

The 2008 financial crisis

Quadruple entry - Government expenditures financed by central bank

	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.		-G		+G		
Income (GDP)	-Y	+Y				
ΔCash					-ΔH	
ΔDep						
ΔBills				-ΔB	+ΔB_{cb}	
sum						

The 2008 financial crisis

Quadruple entry - Government expenditures financed by central bank

	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.		-G		+G		
Income (GDP)	-Y	+Y				
ΔCash					-ΔH	
ΔDep	+ΔM_h					
ΔBills				-ΔB	+ΔB_{cb}	
sum						

The 2008 financial crisis

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Gov. Exp.		-G		+G		
Income (GDP)	-Y	+Y				
ΔCash					$-\Delta H$	
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ΔBills				$-\Delta B$	$+\Delta B_{cb}$	
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Income (GDP)	-Y	+Y				
ΔCash			$+\Delta H_b$		$-\Delta H$	
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sum						

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	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.		-G		+G		0
Income (GDP)	-Y	+Y				0
ΔCash			$+\Delta H_b$		$-\Delta H$	0
ΔDep	$+\Delta M_h$		$-\Delta M$			0
ΔBills				$-\Delta B$	$+\Delta B_{cb}$	0
sum	0	0	0	0	0	0

The 2008 financial crisis

Quadruple entry - Government expenditures financed by private banks

	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.						
Income (GDP)						
ΔCash						
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sum						

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Income (GDP)						
ΔCash						
ΔDep						
ΔBills				-ΔB		
sum						

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	Hh	Prod	Banks	Gov	C.B.	Sum
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sum						

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ΔCash						
ΔDep			-ΔM			
ΔBills			+ΔB_b	-ΔB		
sum						

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	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.						
Income (GDP)						
ΔCash						
ΔDep			-ΔM	+ΔM_g		
ΔBills			+ΔB_b	-ΔB		
sum						

The 2008 financial crisis

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	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.						
Income (GDP)						
ΔCash						
ΔDep			-ΔM	+ΔM_g		0
ΔBills			+ΔB_b	-ΔB		0
sum			0	0		0

The 2008 financial crisis

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	Hh	Prod	Banks	Gov	C.B.	Sum
Gov. Exp.				$+G$		
Income (GDP)						
ΔCash						
ΔDep			$-\Delta M$			
ΔBills			$+\Delta B_b$	$-\Delta B$		
sum						

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ΔCash						
ΔDep			-ΔM			
ΔBills			+ΔB_b	-ΔB		
sum						

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Gov. Exp.		-G		+G		
Income (GDP)	-Y	+Y				
ΔCash						
ΔDep			$-\Delta M$			
ΔBills			$+\Delta B_b$	$-\Delta B$		
sum						

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Income (GDP)	-Y	+Y				
ΔCash						
ΔDep	$+\Delta M_h$		$-\Delta M$			
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Gov. Exp.		-G		+G		0
Income (GDP)	-Y	+Y				0
ΔCash						
ΔDep	$+\Delta M_h$		$-\Delta M$			0
ΔBills			$+\Delta B_b$	$-\Delta B$		0
sum	0	0	0	0		0

The 2008 financial crisis

Quadruple entry - Government expenditures financed by central bank

	Hh	**Prod**	**Banks**	**Gov**	**C.B.**	**Sum**
Gov. Exp.		-G		+G		0
Income (GDP)	-Y	+Y				0
ΔCash			$+\Delta H_b$	$+\Delta H_g$	$-\Delta H$	0
ΔDep	$+\Delta M_h$	$+\Delta M_f$	$-\Delta M$			0
ΔBills				$-\Delta B$	$+\Delta B_{cb}$	0
sum	0	0	0	0	0	0

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- There is a space and a need for policy intervention to mute or to prevent existing or forthcoming imbalances
  - Flexible fractional reserve banking
  - Fisher (1935) 100% money as opposed to current fractional reserve banking: it could have muted the crisis or, even, prevented it to happen.

The 2008 financial crisis

Conclusions

In the context of a financial crisis: *the devil is in the details*fractional reserve banking

The complexity of the crisis requires to explore fine details of the financial system and its feedback to (international) *real* macroeconomics

The 2008 financial crisis

Conclusions

In the context of a financial crisis: *the devil is in the details*fractional reserve banking

The complexity of the crisis requires to explore fine details of the financial system and its feedback to (international) *real* macroeconomics

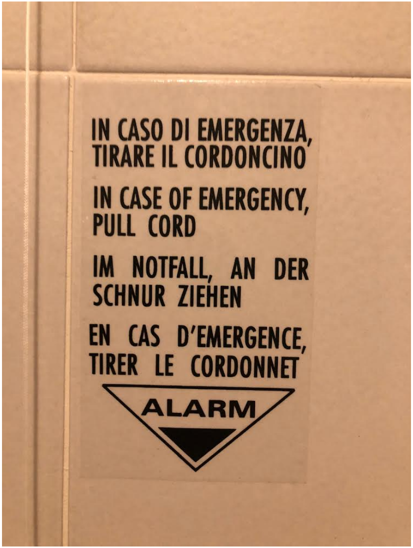
Moreover:

- The law of economics are man-made and can be changed (Gold standard, financialization, quantitative easing, 100% money, etc.)
- Modigliani-Miller does not hold in reality (pecking-order theory)
- *Fundamental uncertainty*

Outlines

What is emergence?

What is emergence?



The atoms

We first describe the accepted rules for individual behaviour. We will then proceed to aggregate them and look for emerging properties

There is a set of possibilities $(x_1, ..., x_D) \in \mathbb{R}_+^D$ (goods) and a set of individuals $n = 1, ..., N$.

Each of them is characterized by a concave utility function $u : \mathbb{R}_+^D \to \mathbb{R}$. He/she will choose according to a maximization rule:

$$\begin{array}{cc} \text{(certain, immediate)} & \max_x u(x) \\ \text{(uncertain, immediate)} & \max_x \mathbb{E}[u(x)] \\ \text{(uncertain, deferred)} & \max_{x(\cdot)} \mathbb{E}\left[\int_0^\infty e^{-rt} u(x(t))\, dt\right] \end{array}$$

In addition, these individuals are *strategic*: they will strive for an *equilibrium outcome*, that is, some choice $(\bar{x}_1, ..., \bar{x}_N)$ such that (Nash):

The consumer model

An individual with utility u is given a sum s to spend and observes a set of prices $p = (p_1, ..., p_D)$. He then solves the problem:

$$\max_x u(x)$$
$$px \leq s$$

Because of concavity, the solution is unique and depends smoothly on p. The resulting map:

$$p \to x(p)$$
$$R^D \to R^D$$

is called the demand function. Note that utility functions cannot be observed, but demand functions can.

Is the model true ?

Early on, Antonell, and later, Slutsky have identified a set of NS conditions that characterize demand functions: the matrix

$$S(x,p) = \frac{\partial x^{\hat{\imath}}}{\partial p_j} + \frac{\partial x^{\hat{\imath}}}{\partial w} x^j$$

should be symmetric and negative definite. These are known as the Slutsky conditions.

Fact : they are tested positively in experiments (Browning-Chiappori)

Aggregation erases all properties

Consider now a group, such as a household. There are now N utility functions, and a common budget constraint. Typically, the individuals will then divide the total budget $s$between themselves in some (unknown and unobserved) way, which may depend on p:

$$s = \sum_{n=1}^{N} s_n$$

so that the problem splits:

$$\max_x u_n(x), px_n \leq s_n$$

and $x(p) = \sum_n x_n(p)$ is the group demand function. Does this group demand have any characteristic property ?
Consider the 1-form $\omega = \sum x^{\imath} dp_i$.

Theorem

(Chiappori-Ekeland) $x(p)$ is a group demand function if and only if

$$\omega \wedge (d\omega)^n = 0$$

The painful truth
MDS-CE

Corollary

If $2n + 1 > 0$, then any map from $\mathbb{R}^D$ into itself is a group demand function

Back to basics

- Interactions not mediated through the market
- Utility-maximizing individuals interacting strategically in other situations
- Schelling: Micromotives and macrobehaviour
- The segregation game: see talk by Ceri in this conference

Mean field games

- Introduced recently by J.M. Lasry and P.L. Lions
- Continuum of agents interacting with their own distribution in space
  - (perfect competition) Each agent is too small to influence the overall distribution: he/she takes it as given
  - (anonimity) Each agent does not care about who the others are, but only where they are: he interacts only with the distribution
  - (emergence) The overall distribution results from the actions of all the agents.
- The result is a fixed-point between the actions of the agents and the overall distribution

An example

We are looking at a continuous family of identical individuals, with total mass 1, trying to place themselves on R^N:

- I want to be away from the others (and possibly close to the ice cream vendor)
- I don't want to walk too far under the sun on the sand carrying my parasol

I control my position by a diffusion, where the trend $a(t)$ is the control and the volatility σ is constant and given:

$$dx = a_t dt + \sigma dW, \ x(0) = x_0$$

I strive to maximize the criterion:

$$\mathcal{V}(t_0, x_0, \mu_0) = \max_a \mathrm{E}\left[V_T(x(T), \mu(T)) + \int_t^T (h(x_t, \mu_t) - g(x_t, a_t))\, ds \right]$$

All agents do the same (but start from different places). Note that this criterion (a) is the same for everyone, but (b) depends on where a particular individual is, and where the others are. The simplifying assumption here is that it depends only on the distribution of individuals on R.

The MFG system

$\mathcal{V}(t,x,\mu)$ must satisfy the HJB equation, where

$$\begin{aligned} 0 &= \frac{\partial \mathcal{V}}{\partial t} + \max_{a(x)} \left\{ \frac{\partial \mathcal{V}}{\partial x} \cdot a + \frac{\sigma^2}{2} \Delta_x \mathcal{V} + h(x,\mu) - g(x,a) + \frac{\partial \mathcal{V}}{\partial \mu} \cdot \frac{d\mu}{dt} \right\} \\ &= \frac{\partial \mathcal{V}}{\partial t} + \frac{\sigma^2}{2} \Delta_x \mathcal{V} + h(x,\mu) + g^* \left(x, \frac{\partial \mathcal{V}}{\partial x} \right) + \frac{\partial \mathcal{V}}{\partial \mu} \cdot \frac{d\mu}{dt} \end{aligned}$$

The evolution of the distribution $\mu(t)$ is given by the Fokker-Planck equation

$$\frac{dm}{dt} = -\mathrm{div}_x (m\bar{a}) + \frac{\sigma^2}{2} \Delta_x m$$

This is the MFG system, one HJB coupled with one FP, one with a terminal condition, one with an initial condition:

$$\mathcal{V}(T, x(T), \mu(T)) = V_T(x(T), \mu(T)), \quad m(0) = m_0$$

The planner's problem

The planner has the means to control the individual decisions $a_t(x)$ and has a collective criterion. Starting from $m(t_0, x) = m_0(x)$, the value is:

$$\begin{aligned} V(t_0, m_0) &= \max_{a_t(\cdot)} \left\{ \int_0^T \left(f(\mu_t) - \int_X g(a_t(y))\, d\mu_t \right) dt + V_T(\mu_T) \right\} \\ \frac{\partial m}{\partial t} &= -\mathrm{div}_x (m a_t) + \frac{\sigma^2}{2} \Delta_x m \end{aligned}$$

HJB is then:

$$0 = \frac{\partial V}{\partial t} + f(\mu) + \max_a \left\{ \frac{\partial V}{\partial m} \cdot \left(\frac{\sigma^2}{2} \Delta_x m - \mathrm{div}_x (ma) \right) - \int_X g(a(y))\, d\mu \right\}$$

Integrating by parts, we get the planner's HJB:

$$0 = \frac{\partial V}{\partial t} + f(\mu) + \frac{\partial V}{\partial m} \cdot \frac{\sigma^2}{2} \Delta_x m + \int_X g^* \left(\frac{\partial}{\partial x} \frac{\partial}{\partial m} V \right) d\mu$$

Comparison 1

$$\mathcal{V} := \frac{\partial V}{\partial \mu}$$

Differentiating HJB, we get:

$$\begin{aligned} 0 &= \frac{\partial \mathcal{V}}{\partial t} + f'(\mu) + \frac{\sigma^2}{2}\Delta_x \mathcal{V} + \frac{\partial \mathcal{V}}{\partial m} \cdot \frac{\sigma^2}{2}\Delta_x m + \\ & \frac{\partial}{\partial m} \max_a \left\{ \int_X \left[\left(\frac{\partial}{\partial x}\frac{\partial}{\partial m} V \right) a - g(a) \right] m dx \right\} \end{aligned}$$

Using the envelope theorem, the last term becomes:

$$\begin{aligned} \int_X \left[-\left(\frac{\partial \mathcal{V}}{\partial m} \right) \mathrm{div}_x (\bar{a} m) + \left(\frac{\partial \mathcal{V}}{\partial x} \right) \bar{a} - g(\bar{a}) \right] dx &= \\ \int_X \left[-\left(\frac{\partial \mathcal{V}}{\partial m} \right) \mathrm{div}_x (\bar{a} m) \right] dx + g^* \left(\frac{\partial \mathcal{V}}{\partial x} \right) &= \end{aligned}$$

Comparison 2

We finally get the equation:

$$0 = \frac{\partial \mathcal{V}}{\partial t} + f'(\mu) + \frac{\sigma^2}{2}\Delta_x \mathcal{V} + \frac{\partial \mathcal{V}}{\partial m} \cdot \frac{\sigma^2}{2}\Delta_x m + g^*\left(\frac{\partial \mathcal{V}}{\partial x}\right) - \int_X \left[\left(\frac{\partial \mathcal{V}}{\partial m}\right) \mathrm{div}_x (\bar{a}m)\right]$$

Compare this with the master equation for the MFG which we obtained earlier:

$$0 = \frac{\partial \mathcal{V}}{dt} + \frac{\sigma^2}{2}\Delta_x \mathcal{V} + h(x,\mu) + g^*\left(x, \frac{\partial \mathcal{V}}{\partial x}\right) + + \frac{\partial \mathcal{V}}{\partial \mu} \cdot \left(\frac{\sigma^2}{2}\Delta_x m - \mathrm{div}_x\left(m \frac{\partial g^*}{\partial v}\left(\right.\right.\right.$$

The solution to the planner's problem, starting from $\mu(0) = \mu_0$

$$\max \left\{ \int_0^T \left(f(\mu_t) - \int_X g(a_t(y))\, d\mu_t \right) dt + V_T(m_T) \right\}$$

can be implemented by the MFG:

$$\max_a \mathrm{E}\left[\frac{\partial V_T}{\partial \mu}(x_T, \mu_T) + \int_t^T \left(f'(\mu_t) - g(a_t)\right) ds \right]$$

An example

Take $f(\mu) = -\frac{1}{2}\int m^2 dx$ and $g(a) = \frac{1}{2}a^2$. Then $h(\mu) = -m$. The (stochastic) individual programs:

$$
\begin{aligned}
&\min_a \mathrm{E}\left[V_T(x_T, \mu_T) + \int_t^T \left(m_t(x_t) + \frac{1}{2}a_t^2\right) dt\right] \\
&dx = a_t dt + \sigma dW_t, \quad \frac{dm}{dt} = \mathrm{div}_x(ma_t) + \frac{\sigma^2}{2}\Delta_x m \\
&x(t_0) = x_0, \ \mu(t_0) = \mu_0
\end{aligned}
$$

realize the optimum of the (deterministic) collective program:

$$
\begin{aligned}
&\min\left\{\frac{1}{2}\int_0^T \int_X \left(m_t^2 + a_t^2 m_t\right) dxdt + \frac{\partial V_T}{\partial m}(m_T)\right\} \\
&m(t_0, x) = m_0(x)
\end{aligned}
$$

Outlines

The trouble with macroeconomics

- Fankhauser-Stern (MIT press, 2016)
  ... we should seek a dynamic economics where we tackle directly issues involving pace and scale of change in the context of major and systemic risks.

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- Kocherlakota (2016)
  ...we simply do not have a settled successful theory of the macroeconomy. The choices made 25-40 years ago - made then for a number of excellent reasons - should not be treated as written in stone or even in pen.

Outlines

A tentative: the Keen model

Theoretical elements

- Minimum (bounded) rationality
- Endogenous business cycles as in the Goodwin model (1967)
- Mathematical formalization of Minsky moment
  - Lotka-Volterra relationship linking the employment rate to the wage share
  - Dynamics of the private debt of firms
- Phenomenological empirical approach to ground aggregated behavior:
  - Short-term Phillips curve (Mankiw (2010), Krugman (2014))
  - Investment function
- Dualism of long-term equilibria:
  - A desirable (Solovian) steady-state equilibrium
  - A bad attractor leading to a breakdown

The model

λ, the employment rate.

$$\lambda := \frac{L}{N}.$$

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w, the wage per worker, $W = wL$, the total wage and Y, the real production define ω, the wage share:

$$\omega = \frac{W}{Y} = \frac{wL}{aL} = \frac{w}{a}$$

Some phenomenological approaches – A tentative: the Keen model

The model

K: the stock of capital.

$$\dot{K} = I - \delta K.$$

Some phenomenological approaches – A tentative: the Keen model

The model

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The Leontief production function

$$\begin{aligned} Y &= \min\left(\frac{K}{\nu}, aL\right) \\ &= \frac{K}{\nu} = aL. \end{aligned}$$

Some phenomenological approaches – A tentative: the Keen model

The model

D: the aggregate debt.

$$\dot{D} = I - \Pi.$$

with $\Pi := Y - W - rD$: the real profit of the firm, and r the interest rate.

π: the profit-to-production ratio.

$$\pi = \frac{\Pi}{Y}.$$

Some phenomenological approaches – A tentative: the Keen model

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d: the debt-production ratio.

$$d = \frac{D}{Y}.$$

Some phenomenological approaches – A tentative: the Keen model

Aggregate behaviours

- The Short-term Phillips Curve (Mankiw, 2010 and Krugman, 2014).

$$\frac{\dot{w}}{w} = \phi(\lambda).$$

Some phenomenological approaches – A tentative: the Keen model

Aggregate behaviours

- The Short-term Phillips Curve (Mankiw, 2010 and Krugman, 2014).

$$\frac{\dot{w}}{w} = \phi(\lambda).$$

- The Investment Function : it evolves positively with the profit share.

$$\frac{I}{Y} = \kappa\left(\pi\right).$$

The three-dimensional system

One can retrieve the following set of equations:

$$
\begin{aligned}
\dot{\omega} &= \omega\left[\phi(\lambda) - \alpha\right] \\
\dot{\lambda} &= \lambda\left[\frac{\kappa(1-\omega-rd)}{\nu} - \delta - \alpha - \beta\right] \\
\dot{d} &= d\left[r - \frac{\kappa(1-\omega-rd)}{\nu} + \delta\right] + \kappa(\pi) - (1-\omega)
\end{aligned}
$$

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Two asymptotically locally stable equilibria:

- $(\bar{\omega}_1, \bar{\lambda}_1, \bar{d}_1)$: The good equilibrium;

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\end{aligned}$$

Two asymptotically locally stable equilibria:

- $(\bar{\omega}_1, \bar{\lambda}_1, \bar{d}_1)$: The good equilibrium;
- $(0, 0, +\infty)$: The bad equilibrium.

Phenomenological approach: $\phi(.)$ and $\kappa(.)$ are empirically estimated.

Convergence to the locally asymptotically stable steady-state equilibrium

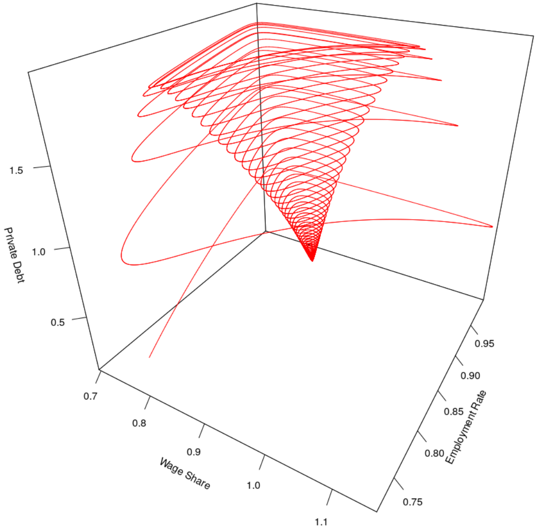


Figure: Phase diagram in the Keen model (1995)

Viability analysis through the basin of attraction

Another view of public policy

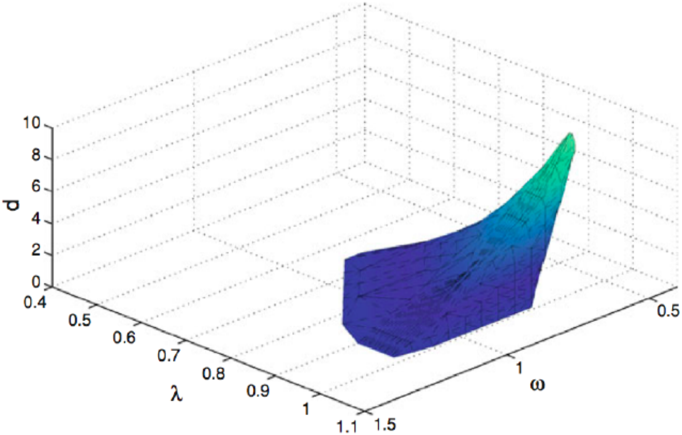
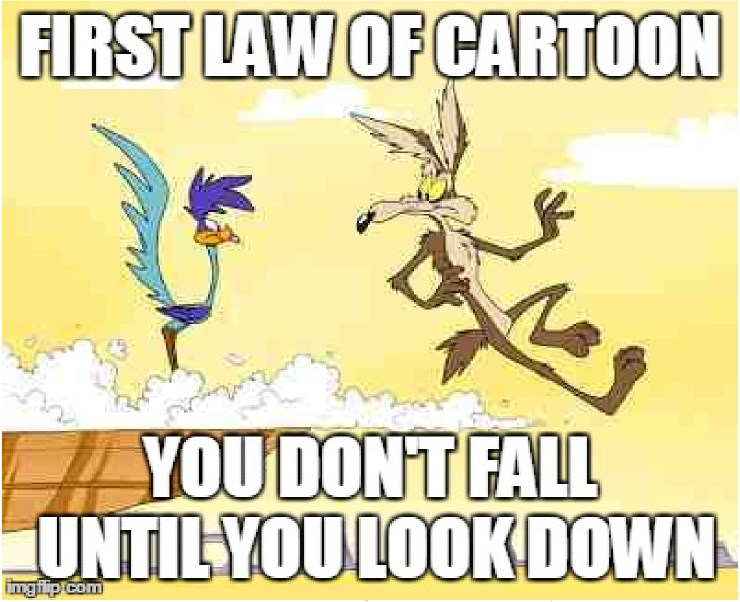


Figure: Basin of attraction of the desirable steady-state in the Keen model. Source: Grasselli *et al*. (2012)

The Minsky Moment



Stock-Flow consistency

	Households	Firms		Banks	Sum
Balance Sheet					
Capital stock		K			K
Deposits	M^h	M^f		$-M$	
Loans		$-L$		L	
Sum (net worth)	X^h	X^f		X^b	X
Transactions		current	capital		
Consumption	$-C$	C			
Investment		I	$-I$		
Accounting memo [GDP]		$[Y]$			
Wages	W	$-W$			
Interests on deposits	rM^h	rM^f		$-rM$	
Interests on loans		$-rL$		rL	
Financial Balances	S^h	Π	$-I$	S^b	
Flow of funds					
Gross Fixed Capital Formation		I			I
Change in Deposits	$\dot{M}^h$	$\dot{M}^f$		$-\dot{M}$	
Change in loans		$-\dot{L}$		$\dot{L}$	
Column sum	S^h	Π		S^b	I
Change in net worth	$\dot{X}^h = S^h$	$\dot{X}^f = \Pi - \delta K$		$\dot{X}^b = \Pi^b$	$\dot{X}$

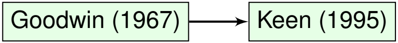
Table: Balance sheet, transactions, and flow of funds in the economy

Outlines

The modelling tree

Goodwin (1967)

The modelling tree



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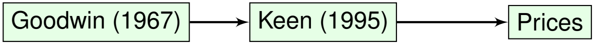

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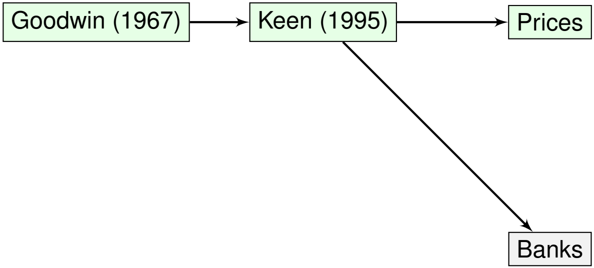

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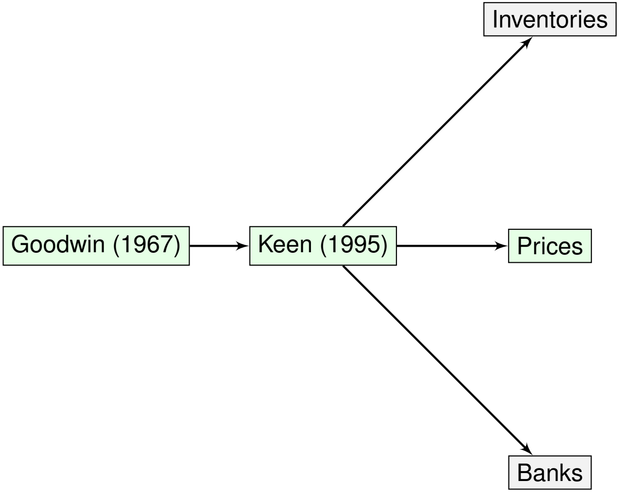

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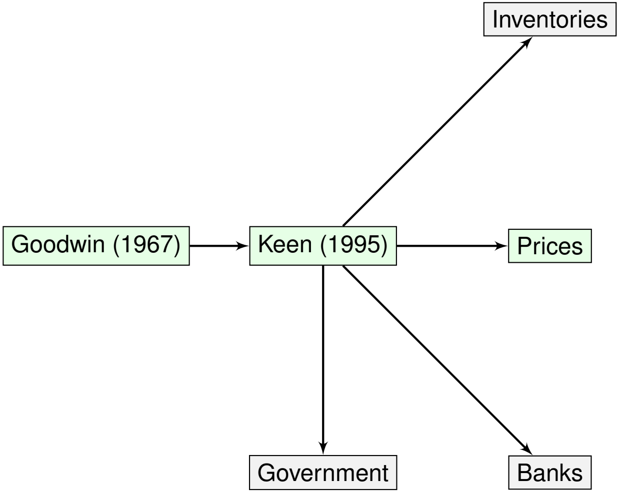

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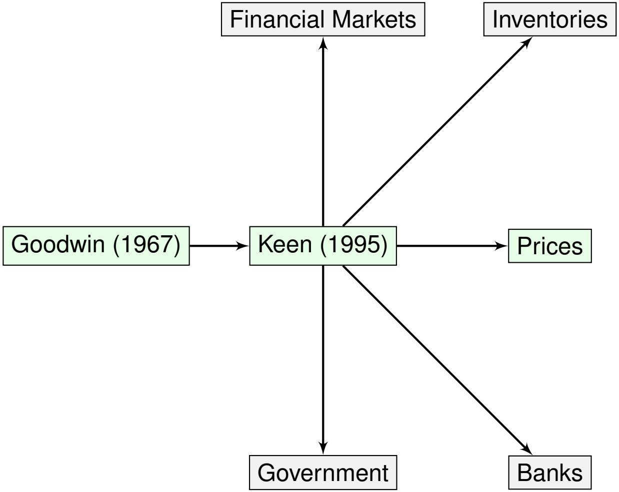

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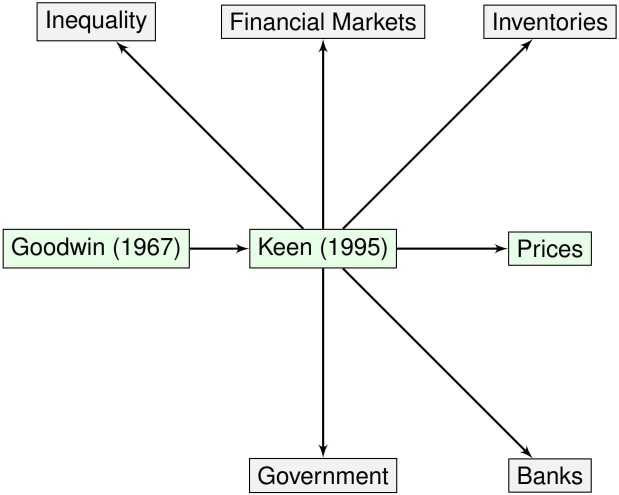

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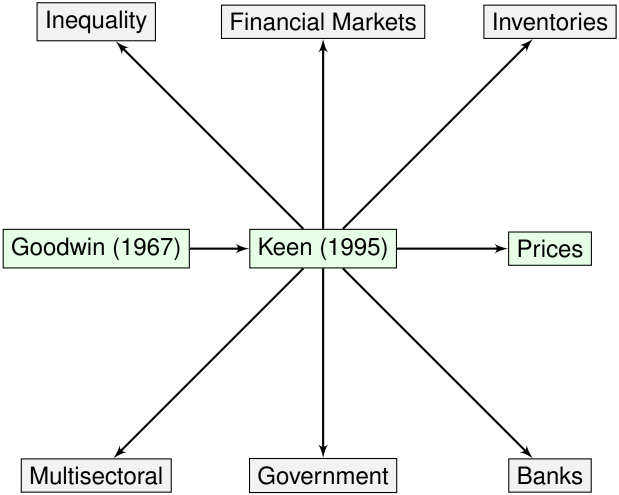

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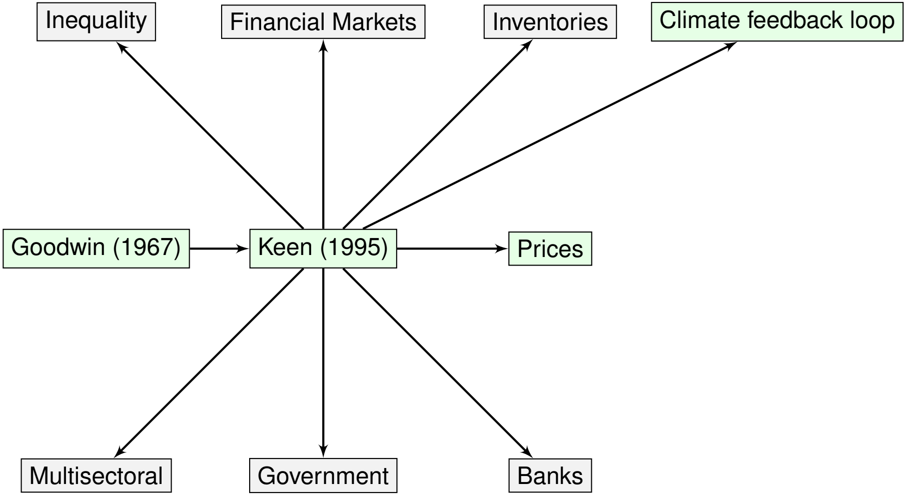

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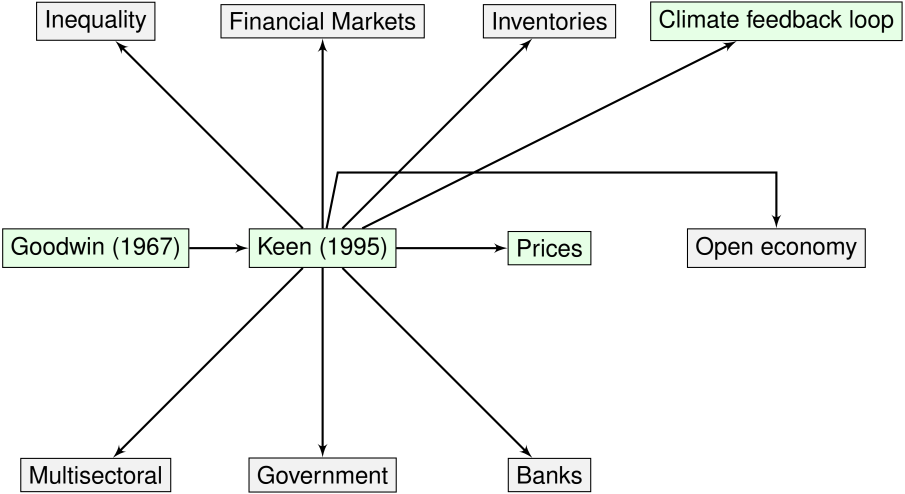
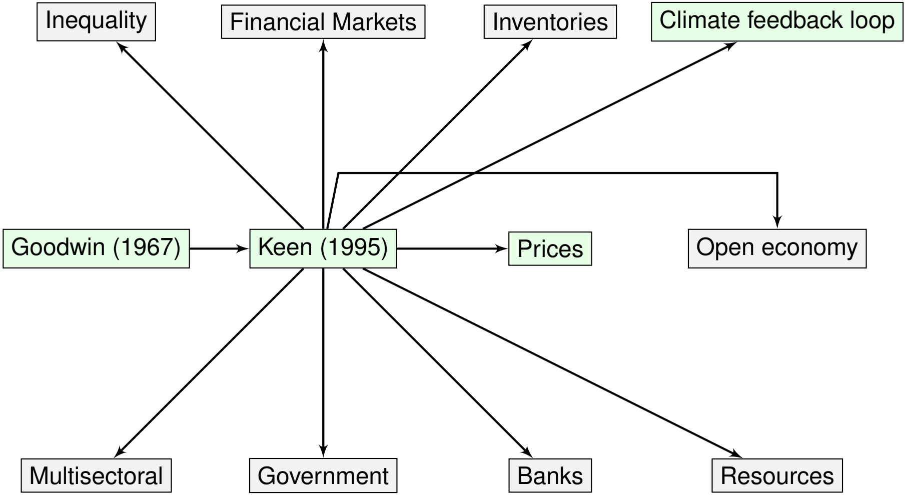


The modelling tree



An example: Coping With Collapse

Bridging climate and a global monetary economy

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Bridging climate and a global monetary economy

1. The macroeconomic core
   - Non-neutrality of money
   - Severe breakdowns do not appear as “black swan events”
   - Emissions, carbon price and abatement technology (Nordhaus, 2016)
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   - Sigmoïd pattern of the global workforce (UN population scenarios, 2015)
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2. The DICE climate feedback loop of Nordhaus (2016) refined with
   - More convex damage functions (Weitzman, 2011)
   - Allocation of environmental damages between output and capital (Dietz *et al.*, 2015)

Dynamics and behavioural relations

- Short term Phillips curve: $\frac{\dot{w}}{w} = \phi(\lambda)$
- Dynamic of prices (Grasselli *et al.*, 2014): $\frac{\dot{p}}{p} = \eta(m\omega - 1)$
- Investment behavior: $I = \kappa(\pi)$
- Dynamics of private debt: $\dot{D} = I - \Pi - \Pi_r$
- Taylor rule: $r = \max\{0, r^* + i + \phi(i - i^*)\}$
- Dynamics of capital: $\dot{K} = I - (\delta + \mathbf{D}^K)K$

Introducing climate change and public policies

- Joint production process incorporating climate damages

$$Y^0 = \min\{K/\nu; aL\}$$

$$Y = (1 - \mathbf{D}^{\mathrm{Y}})\big(1 - A(p_{BS})\big)\, Y^0$$

$$E_{ind} = \sigma\big(1 - n(A)\big)\, Y^0$$

- Public policies and aggregated profit

$$\Pi = pY - wL - rD - pT(p_C, E_{ind}) - (\delta + \mathbf{D}^{\mathrm{K}})pK,$$

- Endogenous choice of the emission reduction rate in the productive sector

$$n = \min\left\{\left(\frac{p_c}{p_{BS}}\right)^{\frac{1}{\theta - 1}}; 1\right\}$$

Stock-flow consistency

	Households	Productive Sector		Banks	Sum
Balance Sheet					
Capital stock		pK			pK
Deposits	M^h	M^c		$-M$	
Loans		$-L_c$		L_c	
Equities	E	$-E^f$		$-E^b$	
Sum (net worth)	X^h	$X^f = 0$		$X^b = 0$	X
Transactions		current	capital		
Consumption	$-pC$	pC			
Investment		pI	$-pI$		
Acc. memo [GDP]		$[pY]$			
Wages	W	$-W$			
Capital depr.		$-(\delta + \mathbf{D}^{\mathrm{K}})pK$	$(\delta + \mathbf{D}^{\mathrm{K}})pK$		
Carbon taxes	pT_f	$-pT_f$			
Int. on loans		$-r_c L_c$		$r_c L_c$	
Bank's dividends	Π_b			$-\Pi_b$	
Productive sector's dividends	Π_d	$-\Pi_d$			
Int. on deposits	$r_M M^h$	$r_M M^c$		$-r_M M$	
Column sum (balance)	S^h	S^c	$-pI + (\delta + \mathbf{D}^{\mathrm{K}})pK$	S^b	
Flow of Funds					
Change in capital stock		$p\dot{K}$			$p\dot{K}$
Change in deposits	$\dot{M}^h$	$\dot{M}^c$		$-\dot{M}$	
Change in loans		$-\dot{L}_c$		$\dot{L}_c$	
Column sum (savings)	S^h	S^c		S^b	
Change in equities	$\dot{E}^f$	$-(S^c + \dot{p}K)$			
Change in bank equity	$\dot{E}^b$			$-S^b$	
Change in net worth	$S^h + \dot{E}$	0		0	$\dot{p}K + p\dot{K}$

Physical process overview

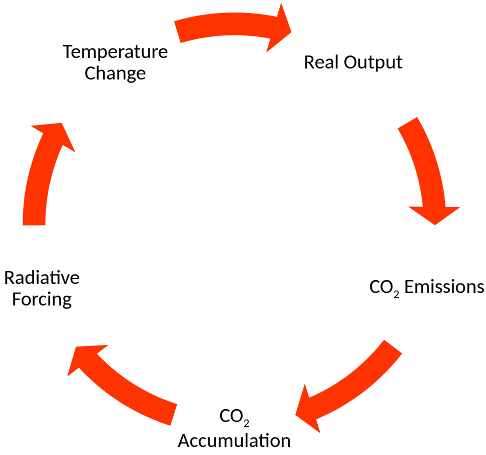

Figure: Climate-economy interactions diagram.

Design of the prospective scenarios

- Calibration over a reconstructed world economy (approx. 85% of the "real" world) with a panel of 36 countries over the period 2000 – 2015 (dataset from World Bank, Penn University, the Bureau of Economic Analysis and the United Nations).
- Prospective analysis through 4 classes of scenarios:[1]

Scenario	**No climate**	**Baseline**	**Low policy**	**High policy**
Carbon tax (Weak p_C)	-	Yes	-	-
Carbon tax (High p_C)	-	-	Yes	Yes
Abat. subsidy (25%)	-	-	-	Yes
Damage Type	-	Stern	Stern	Stern

Table: Scenarios considered for the prospective analysis

[1] The scenarios listed in the presentation are drawn from a broader range assessed in this study.

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Table: Scenarios considered for the prospective analysis

- Where the public policies are
  1. Weak p_C represents non-constraining carbon price starting at approx. 2 in 2016 and growing at a 2% rate per year
  2. High p_C represents a carbon price at 80 in 2020 and 100 in 2030
  3. A x% of abatement subsidy in equivalent to reducing abatements costs by x%

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The no-climate scenario

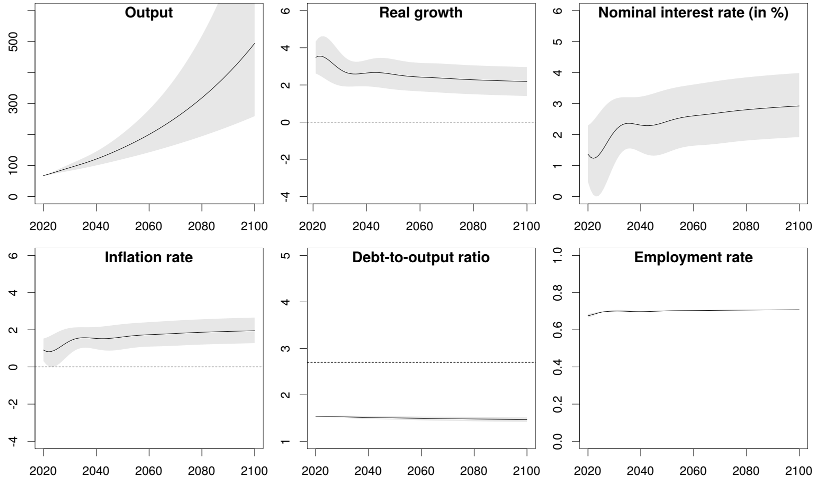

Figure: [0.25; 0.75] probability interval of the **No climate** scenario with a damage-to-capital ratio of 0% in black shades (medians in solid lines)

Policy scenarios – Trajectories and narratives

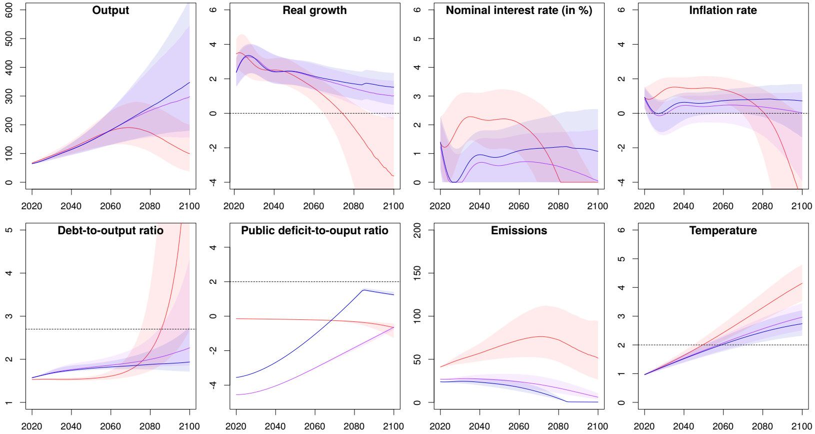

Figure: [0.25; 0.75] probability interval of the **Baseline**, **Low policy** and **High policy** scenarios with a damage-to-capital ratio of 0% in red, purple and blue shades (medians in solid lines)

Policy scenarios – Basin of attraction

Ecological Economics 147 (2018) 383–398

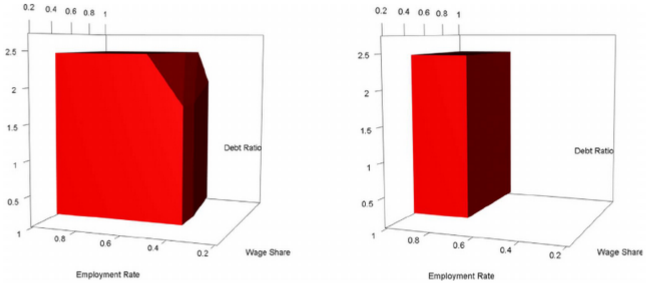

Fig. 3. "Good" basins of attraction in the *No feedback loop scenario* (left) and in the *Low damage scenario* (right).

Concluding remarks

- Development of a stock-flow consistent monetary integrated assessment model calibrated at the world level
- Inaction would most likely lead to a global collapse of the economic system
- A limited action (carbon price only) allows to avoid most climate damages but remains insufficient to preclude financial instability
- A wider public involvement (carbon price and subsidies) is more likely to meet both objectives, in line with the recommendations of the Stern-Stiglitz report (2017)

Outlines

Gabaix, 2016

Let's start with a story

- Paul Samuelson (1969) was once asked by a physicist for a law in economics that was both nontrivial and true.

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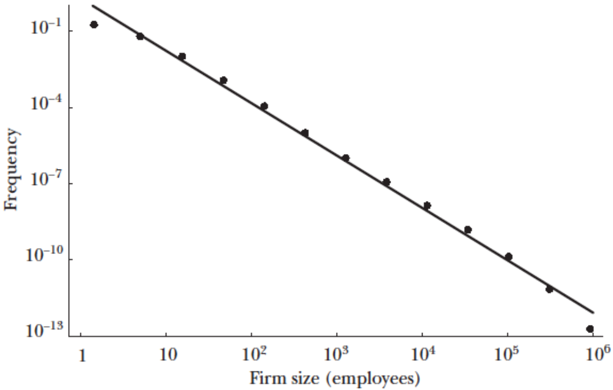
- Gabaix's answer: Power laws

Ex 1: Firms

Figure 3

Log *Frequency* versus log *Size* of US firms (by Number of Employees) for 1997

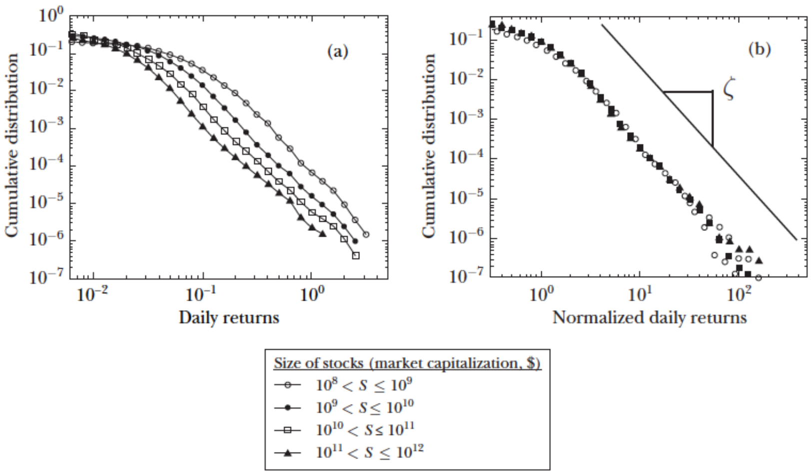


Source: Axtell (2001).
Notes: Ordinary least squares (OLS) fit gives a slope of 2.06 (s.e. = 0.054; $R^2 = 0.99$). This corresponds to a frequency $f(S) \sim S^{-2.059}$, which is a power law distribution with exponent 1.059. This is very close to an ideal Zipf's law, which would have an exponent $\zeta = 1$.

Ex 2: Stock markets returns

Figure 4

Cumulative Distribution of Daily Stock Market Returns for Different Sizes of Stocks



Ex 3: Distribution of income and wealth

- First observed by Pareto in (at least) 1896;
- Typically, the Pareto exponent is 1.5 for wealth
- and between 1.5 and 3 for income

What causes Power Laws?

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- Proportional random growth *plus* lower threshold (friction)–constant return to scale, or not so increasing return to scale
- Matching and Economics of Superstars (CEOs):

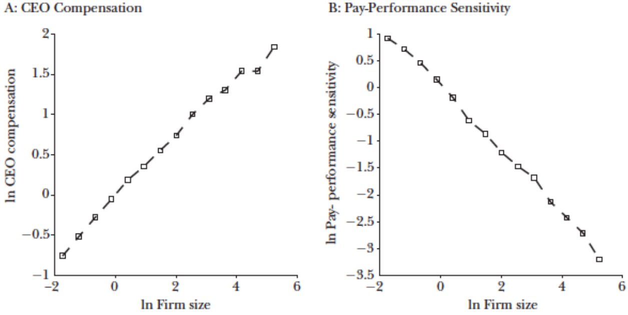
$$w(n) = D(n^*)S(n^*)^{1-b}S(n)^b$$

  - $w(n)$ is the pay of CEO number n
  - $D(n^*)$ is a constant that depends on model parameters
  - $S(n^*)$ is the size of a reference firm

Ex 3: CEO

Figure 5

CEO Pay and CEO Pay–Performance Sensitivity versus Firm Size



Source: The data and methodology is from Edmans, Gabaix, and Landier (2009), for the years 1994–2008. Years are lumped together by reporting $\ln \frac{w_{it}}{\overline{w}_t}$ (panel A) and $\ln \frac{PPS_{it}}{\overline{PPS}_t}$ (panel B) versus $\ln \frac{S_{it}}{\overline{S}_t}$ (horizontal axis in both panels), where $\overline{x}_t$ indicate the median value of x_{it} in year t.

Notes: Left panel: The CEO compensation is the ex ante one, including Black–Scholes value of options granted. The slope is about 1/3, a reflection of Roberts's law: Pay ~ Size^b with $b \simeq 1/3$. Right panel: The pay–performance sensitivity (PPS) is the Jensen–Murphy measure: by how many dollars does the CEO wealth change, for a given dollar change in firm value. The slope is about −2/3, so that PPS ~ Size^{b-1} with $b \simeq 1/3$. The congruence between the scalings is predicted by the Edmans, Gabaix, Landier (2009) model.

Figure: Gabaix, 2016

Granularity: Aggregate Fluctuations from Microeconomic Shocks

Where do aggregate fluctuations come from?

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Is this granular hypothesis relevant empirically? Yes: In the US, shocks to large firms explain about 1/3 of GDP fluctuations (Gabaix, 2011). In France, it is about 1/2 (Di Giovanni, Levchenko, and Mejean, 2014).

Granularity along the time

- The Great Moderation: came about in part because of the shrinkage of a handful of heavy-manufacturing sectors in the 1970s, whose demise made the economy more diversified.
- While the 1970s: importance of the energy sector to which the economy was strongly dependent
- From this view, the growth in the size of the financial sector is an important determinant of the increase in fundamental volatility—and of actual volatility—in the 2000s.

Outlines

- Schumpeter: Credit creation as the "monetary complement of innovation"

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The carrying into effect of an innovation involves, not primarily an increase in existing factors of production, but the shifting of existing factors from old to new uses. [...] If innovation is financed by credit creation, the shifting of the factors is effected not by the withdrawal of funds - "canceling the old order"- from the old firms, but by the reduction of the purchasing power of existing funds which are left with the old firms while newly created funds are put at the disposal of entrepreneurs: the new "order to the factors" comes, as it were, on top of the old one, which is not thereby canceled. (Schumpeter, 1939, pp. 110-111)

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3. Has an impact on labor markets,
4. Changes income distribution,
5. Shifts consumption preferences.

Periodisation of Schumpeter innovation cycle

1. Start with ‘circular flow’
   - economy reproduces itself
2. Emergence of entrepreneurs
   - Credit creation
   - Re-allocation of purchasing power
   - Inflationary
3. Establishment of innovation
   - At first profit for old sectors on aggregate
   - Deflationary pressure (productivity and credit destruction)
   - Creative destruction
4. New equilibrium

Trajectory of an individual technology

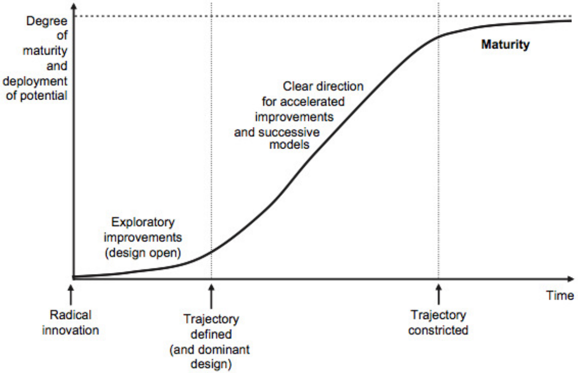

Fig. 1. *The trajectory of an individual technology.*
Source: based on Wolf (1912), Utterback and Abernathy (1975), Nelson and Winter (1977), Metcalfe (1979), Dosi (1982), Arthur (1988), Malerba (1992) etc.

Production and Financial Capital

Schumpeter: complementary

Financial capital follows a pecking-order theory, as for productive capital. Furthermore, criteria are influenced by techno-economic paradigms.

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Fundamental differences

- Path-dependency for productive capital and is intrinsic to the techno-economic paradigm. Long-term horizon
- Financial capital is "footloose, flexible, and mobile". Distribution of wealth in order to obtain financial returns on the short term.

Transitions as the emergence of new techno-economic paradigms

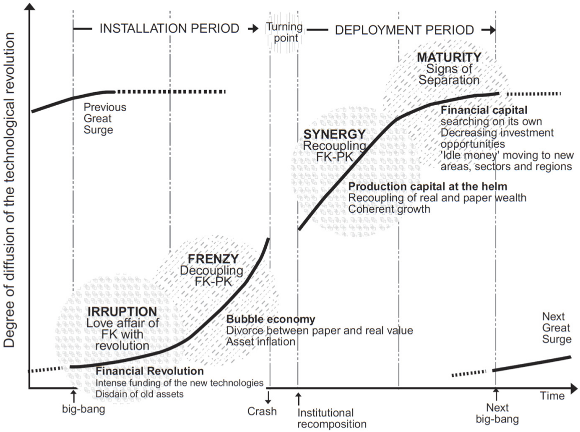
Perez (2002,2009,2010)

Three deeply interlocked dynamics:

1. long-run real-institutional process emerging from the re-structuring of the productive sector
2. short-run financial process driven by the creation of credit at the roots of innovation
3. behavioral medium-run process emerging from the interaction between new financial behaviors and the institutional response

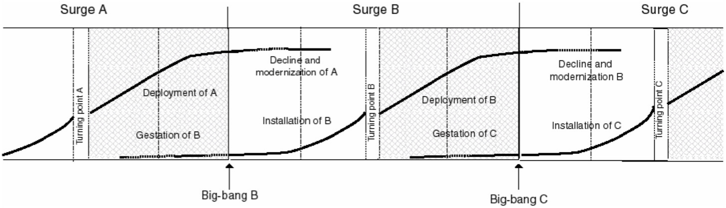
Production and Financial Capital

The recurring sequence in the relationship between financial capital (FK) and production capital (PK)



Overlapping–creative destruction

Figure 3 The overlaps in the gestation, diffusion and decline of successive surges[30]



Thank you!

"All models are wrong, some are useful" G. Box