The direction of technical change in AI and the trajectory effects of government funding

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Public funding and the direction of technical change

- Government and technical change:

  Due to market failures in the production of knowledge (Nelson, 1959; Arrow, 1962), governments play a crucial role in creating incentives and supporting R&D activities in the economy (Bloom et al., 2019).

- Growing interest on the role of public funding:

  While the economic literature focused on firm R&D investments and their spillover effects (Azoulay et al., 2019), the interest in the role of public funding is growing since uncoordinated private investments in new technologies might be insufficient to face complex societal challenges (Mazzucato, 2015; Van Reenen, 2020).

- Existing literature studied the impact of public funding on the rate of technical change:

  Rate of returns of R&D investments (Hall et al., 2010); Policy evaluations of the effects of R&D subsidies (Bloom et al., 2002; Wilson, 2009; Dechezlepretre et al., 2016; Akcigit et al., 2018) and government grants (Bronzini and Iachini, 2014; Howell, 2017; Santoleri et al., 2020) on private innovation outcomes.

- Relatively little (systematic, quantitative) evidence on the role of public funding on the direction of technical change:

  Difficult to evaluate outcomes that are produced over the long-run especially by early interventions (Dosi, 1988; Griliches, 1992).

AI as General Purpose Technology

- AI involves "[the automation of] activities that we associate with human thinking, activities such as decision-making, problem-solving, learning. . . " (Bellman, 1978).

- AI is a likely candidate as the dominant general purpose technology (GPT) of the coming era (Cockburn et al., 2018; Martinelli et al., 2021): it will favor deep transformations in economic systems (Bresnahan and Trajtenberg, 1995) and could generate waves of radical innovations leading to widespread economic disruption (Trajtenberg, 2019).

- AI may affect the economy in several ways: it might have a direct effect on growth and labor (Acemoglu and Restrepo, 2018; Aghion et al. 2017; Furman and Seamans, 2018; Korinek and Stiglitz, 2019) as well as change the innovation process itself (Cockburn et al., 2018) and the industrial structure (Varian, 2018).

- The effects of technological transformation can only be understood if we open up the "black box" of technology, and examine how, where, and why technologies emerge and evolve (Rosenberg, 1982).

- The role of government may be important for this kind of GPTs because their development is very risky and, therefore, either very costly or simply impossible to finance by means of private funds, given the uncertainty and time-horizons of returns.

Research questions

- What has been the role of government funding on the direction of AI development?
- Did the type of funding (government grants vs. government-led research) matter?
- Did the effects change over time?

Direction of technical change: technological trajectories

- Cumulativeness of technical change (Dosi, 1982; Dosi, 1988):

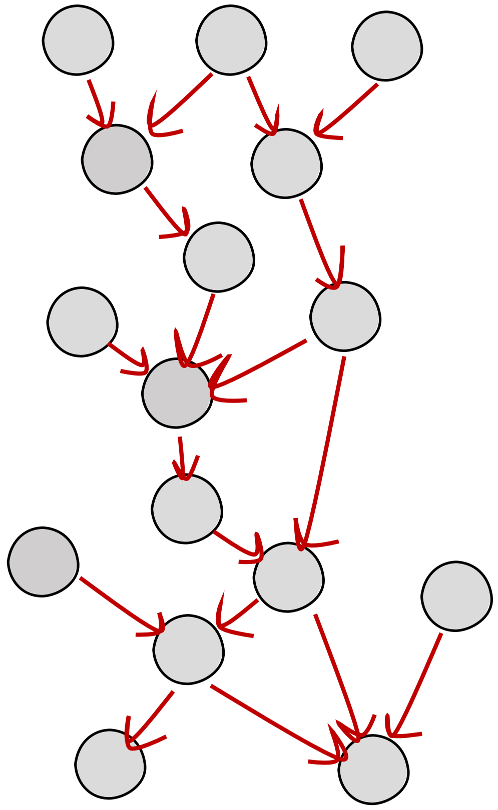
New knowledge builds on prior knowledge, often in a recombinatory way (Weitzman, 1998; Wuchty et al., 2007).

- Evolutionary process:

Over time, it should select in more useful and valuable knowledge, on which further knowledge will be built, and select out less valuable or obsolete knowledge.

- Patterns of cumulative change:

Technological trajectories emerge over time. They can be viewed in retrospect as the path-dependent outcome of dispersed research efforts converging into particular ways of solving problems (Dosi, 1988).



We will test whether the government plays a role in directing technical change and influencing the patterns of knowledge accumulation.

Data: AI-related patents granted by the USPTO

We use patents:

- As indicators of innovation activities (Hall et al., 2001).
- Granted by the USPTO from 1976 to 2019 (EPO-PATSTAT database, Autumn 2019 version).
- Related to AI: we combine search for specific technological classes (CPC) with a text-based search of technical keywords on patent titles and abstracts (WIPO, 2019; UKIPO, 2014).

Advantages of patent data:

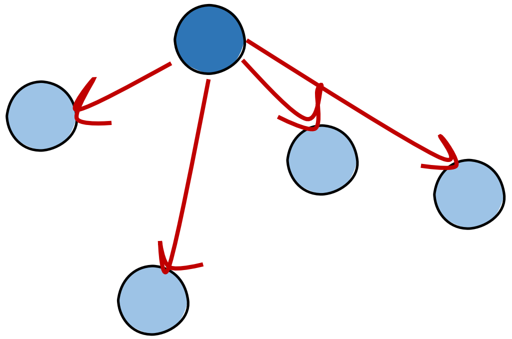
- We exploit patent citation network to track the technological evolution of the field.
- We identify government-funded patents (Fleming et al., 2019):
  - Government assignee patents: Patents assigned to federal agencies, national laboratories, and state departments (EPO-PATSTAT and Patentsview disambiguation of assignee and applicant categories)
  - Government interest patents: Inventions developed with federal funding (Government Interest Statement: Bayh-Dole Act, 1980)

USPTO patents in AI

- We select 114,670 USPTO patents connected through directed and undirected citations that respect the time flow.
- They mainly belong to computer technologies and control systems engineering: most patents concern image analysis, speech recognition, and data processing in general.
- The leading assignees are well-known information and communication technology companies: International Business Machines Corporation, AT&T Corporation, Microsoft, Google, and Amazon.
- We observe 929 patents with government assignees and 3597 patents that received government funding through grants.
- The Department of Defense is, by far, the primary supporter of AI research.

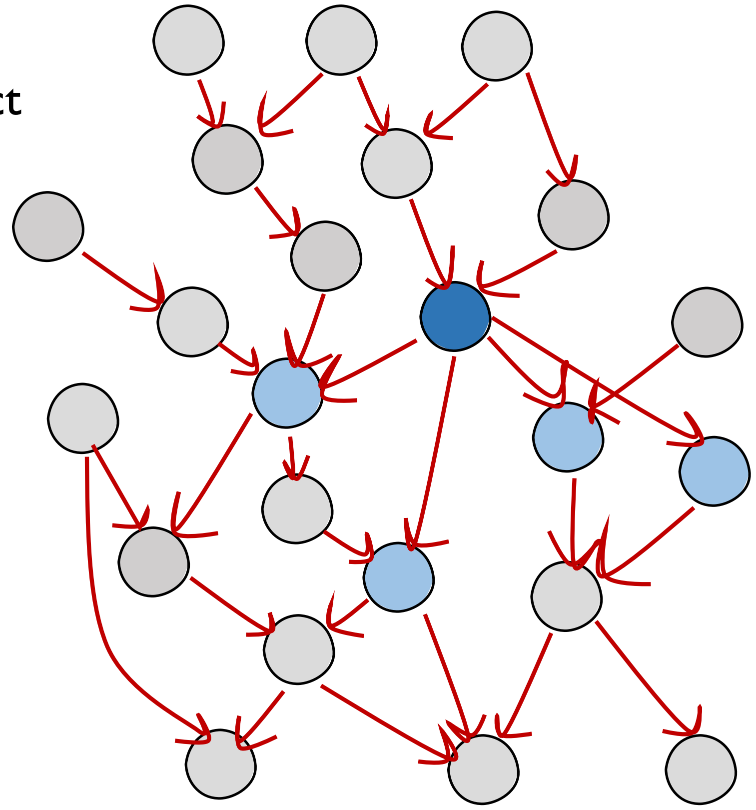
The need for new indicators: short-run vs. long-run impact of inventions

Number of citations



Long-term cumulative impact of new knowledge is not captured by standard patent citation measures

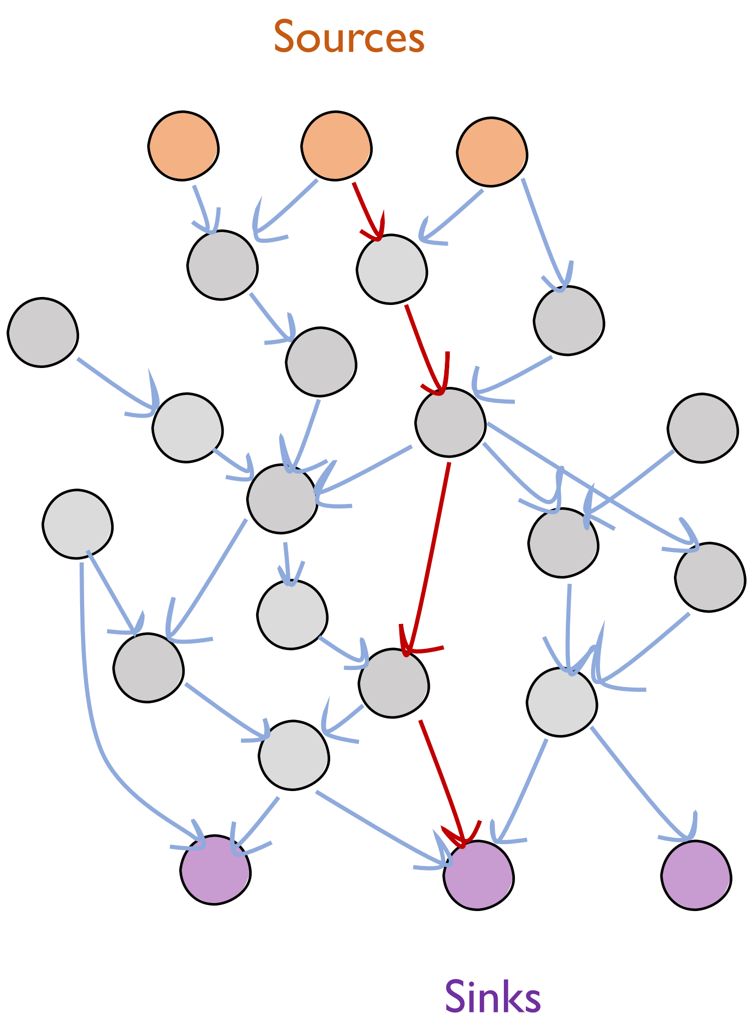
Trajectory effect



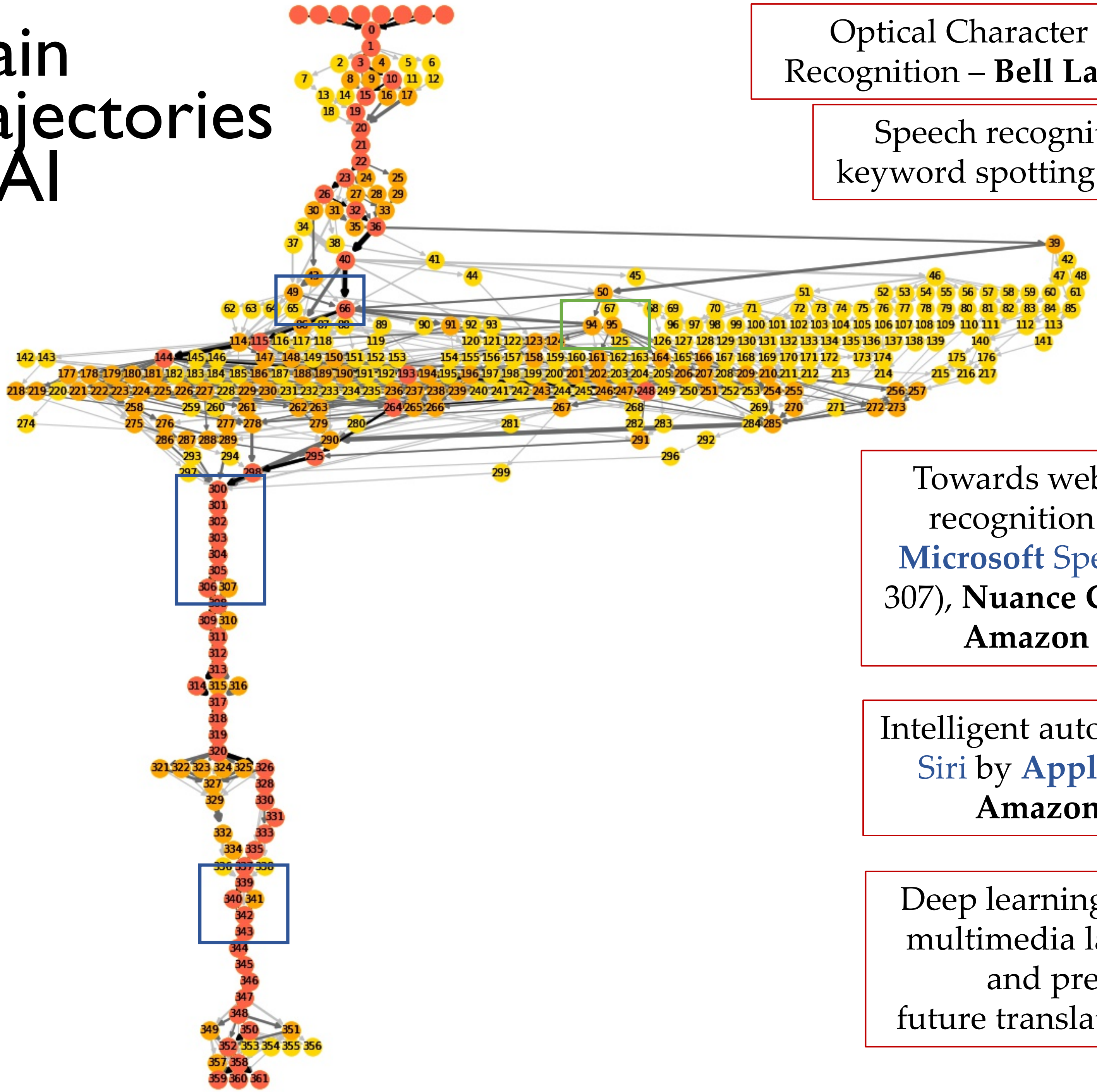
Citation networks: chains of local, cumulative, and irreversible technological developments, consistently with the definition of technological trajectories (Dosi, 1982; Verspagen, 2007)

New indicators to measure trajectory effect (I)

- We create a citation network of 514,599 nodes and 2,661,528 edges from AI inventions and their references.
- Citations respect the time flow and there are no loops: Directed Acyclic Graph (DAG).
- In DAG, it is possible to define paths from sources to sinks without encountering each node more than once.
- Connectivity indicators (Hummon and Dereian, 1989; Batagelj, 2003): Search Path Count assigns to each edge (u; v) a weight equal to the number of paths from s to t through (u; v).
- The higher the weight, the more important the edge is for network connectivity and the development of the entire technological domain.
- Early explorations of this methodology (Mina et al., 2007; Martinelli, 2012) used traversal counts to identify the most relevant trajectories in small technological domains.



Main trajectories in AI



Optical Character Recognition – **Bell Labs**

Early 1950s

Speech recognition: templates and keyword spotting – **Bell Labs** and **NEC**

1950s – 1970s

Speech recognition: probabilistic learning – Hidden Markov Models at **Bell Labs** (49) and **IBM** (66) – and first commercial software by **Dragon Systems** (88,94,95)

1980s

Speech recognition: towards Natural Language Processing

1990s

2000

Towards web-based speech-recognition applications – **Microsoft** Speech Server (300-307), **Nuance Communications**, **Amazon** and **Google**

Intelligent automatic assistants – Siri by **Apple** (339-343) and **Amazon** Echo (344)

2010

Deep learning: applications in multimedia language context and predictions of future translations – **Facebook**

2015

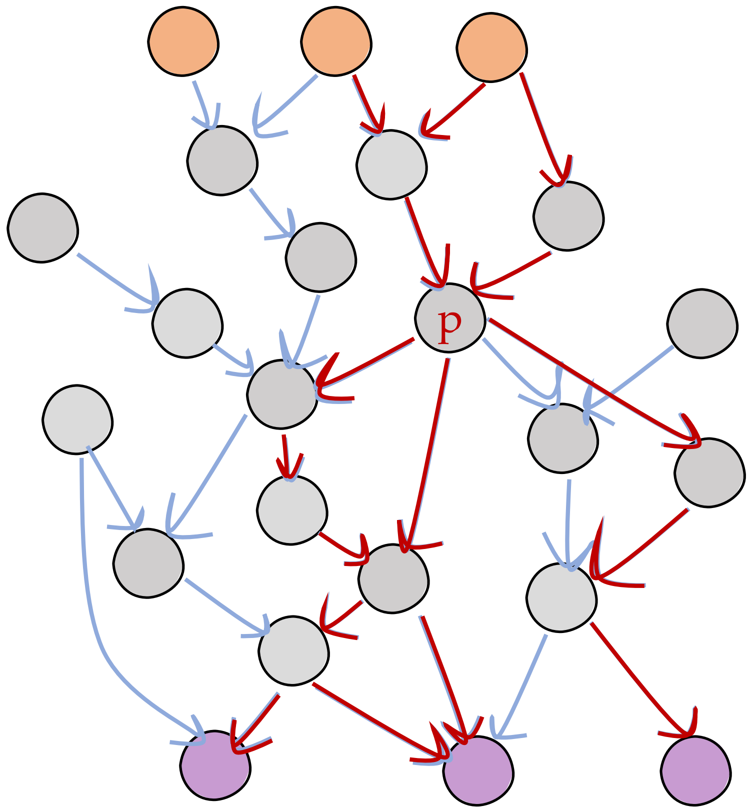
New indicators to measure trajectory effect (II)

- We can extend the methodology to the nodes of the network to measure the relevance of a single patent from a trajectory perspective.

- Trajectory effect: this measure indicates the number of paths from s to t through the patent p.

- A patent with a high weight is a patent that "cumulates" a large knowledge flow within the network.

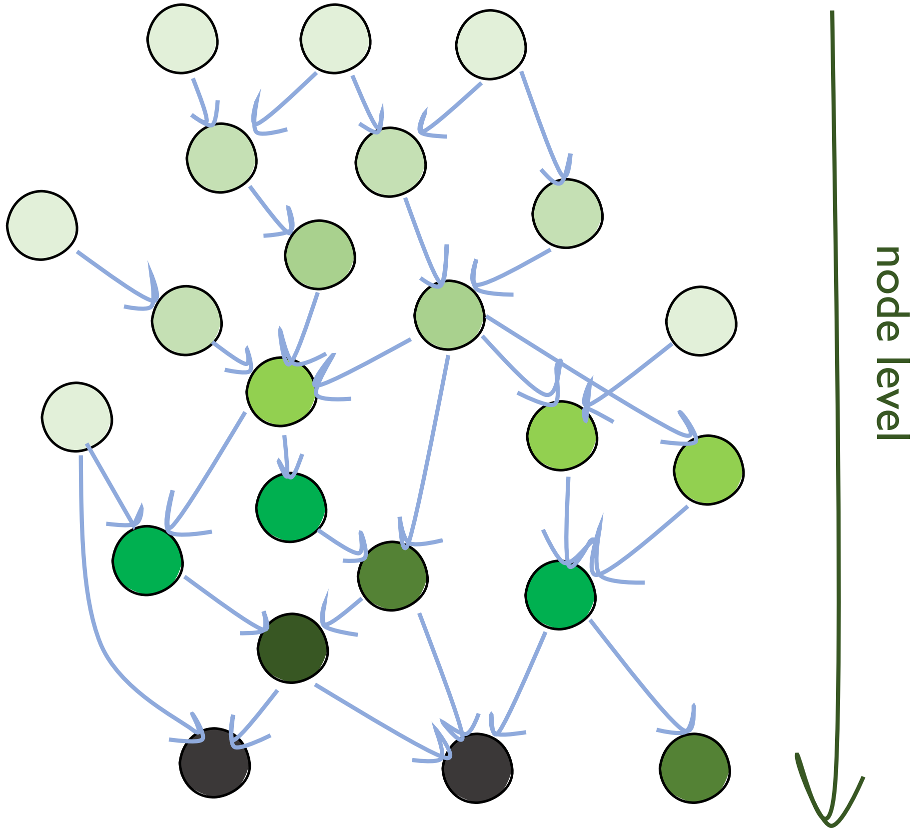
Sources



Sinks

Time in citation networks: the node level indicator

- Indicator of timing in directed citation network: node position (distance from the sources) in the graph.
- Node level indicator marks time in terms of the patent citation network and overall evolution of the field.
- Node level takes value 0 for network sources and, for all the other patents, it is equal to 1 plus the maximum node level of their cited patents.
- Low values refer to the early stages of the technology (i.e., closer to sources).
- High values indicate innovations in a mature phase (i.e., closer to sinks).



Estimating the role of government funding on the trajectory effect

We estimate, for patent p in technological class i, the following baseline specification:

$$\begin{aligned} Ln(\text{trajectory effect}_{pi}) = & \beta_0 + \beta_1 \text{ government funding}_p \\ & + \beta_2 \text{ government funding}_p \times \text{timing}_p \\ & + \beta_3 \text{ timing}_p + \gamma_p + \delta_i + \epsilon_{pi}, \end{aligned}$$

We add:

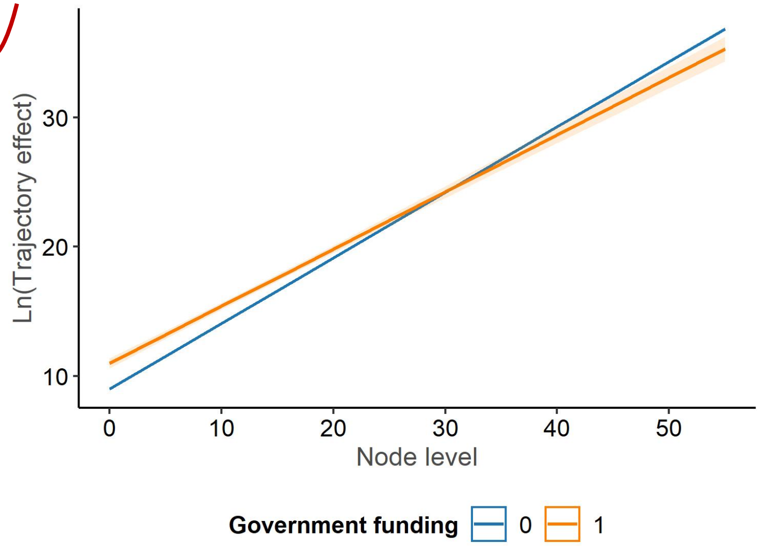
- Controls at the patent level: number of claims, inventors' team size, US university as assignee (dummy).
- Sub-field (3-digits CPC) fixed effects to control for diverse citation behavior in different fields.

The role of government funding - Results

	Dependent variable:		
	log(Trajectory effect)		
	(1)	(2)	(3)
Government funding	1.184***	1.096***	1.959***
	(0.132)	(0.147)	(0.263)
Government funding*Timing			-0.064***
			(0.011)
US university		0.272	0.282*
		(0.166)	(0.166)
Timing	0.503***	0.503***	0.505***
	(0.002)	(0.002)	(0.002)
Number of claims	0.043***	0.043***	0.043***
	(0.002)	(0.002)	(0.002)
Number of inventors	-0.106***	-0.106***	-0.106***
	(0.011)	(0.011)	(0.011)
Intercept	8.594***	8.592***	8.562***
	(0.078)	(0.078)	(0.078)
3-digit CPC	Yes	Yes	Yes
Observations	114,670	114,670	114,670
R^2	0.435	0.435	0.435
Adjusted R^2	0.435	0.435	0.435
Residual Std. Error	7.292	7.292	7.291
F Statistic	3078.115***	3008.006***	2951.426***

Note: All the models are estimated using OLS.
Robust standard errors are reported in parenthesis.
Legend: *p<0.1; **p<0.05; ***p<0.01

Patents receiving government funding have, on average, a trajectory effect 223.9% higher than other patents



Government grants vs. government inventions

Patents receiving government grants have, on average, a trajectory effect 164.9% higher than other patents

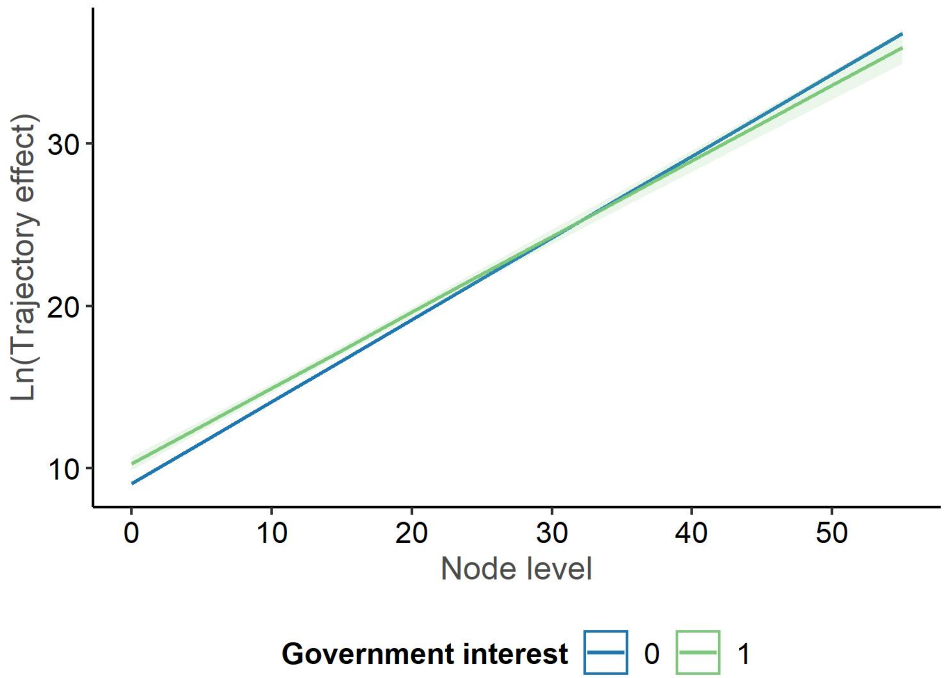
	Dependent variable:					
	log(Trajectory effect)					
	(1)	(2)	(3)	(4)	(5)	(6)
Government interest	0.983***		0.460***	0.999***	0.481***	0.622**
	(0.134)		(0.157)	(0.281)	(0.156)	(0.288)
Government interest*Timing				-0.037***		-0.010
				(0.012)		(0.012)
Government assignee		2.322***	2.050***	1.959***	4.323***	4.233***
		(0.321)	(0.338)	(0.340)	(0.537)	(0.562)
Government assignee*Timing					-0.230***	-0.224***
					(0.030)	(0.031)
US university			0.551***	0.541***	0.551***	0.548***
			(0.168)	(0.168)	(0.167)	(0.168)
Timing	0.503***	0.503***	0.504***	0.505***	0.505***	0.505***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Number of claims	0.043***	0.043***	0.043***	0.043***	0.043***	0.043***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Number of inventors	-0.106***	-0.102***	-0.104***	-0.104***	-0.105***	-0.105***
	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)
Intercept	8.610***	8.597***	8.574***	8.560***	8.555***	8.551***
	(0.078)	(0.078)	(0.078)	(0.078)	(0.078)	(0.078)
3-digit CPC	Yes	Yes	Yes	Yes	Yes	Yes
Observations	114,670	114,670	114,670	114,670	114,670	114,670
R^2	0.435	0.435	0.435	0.435	0.435	0.435
Adjusted R^2	0.435	0.435	0.435	0.435	0.435	0.435
Residual Std. Error	7.294	7.293	7.291	7.291	7.289	7.289
F Statistic	3074.472***	3078.966***	2944.038***	2886.062***	2891.010***	2831.363***

Note: All the models are estimated using OLS.
Robust standard errors are reported in parenthesis.
Legend: *p<0.1; **p<0.05; ***p<0.01

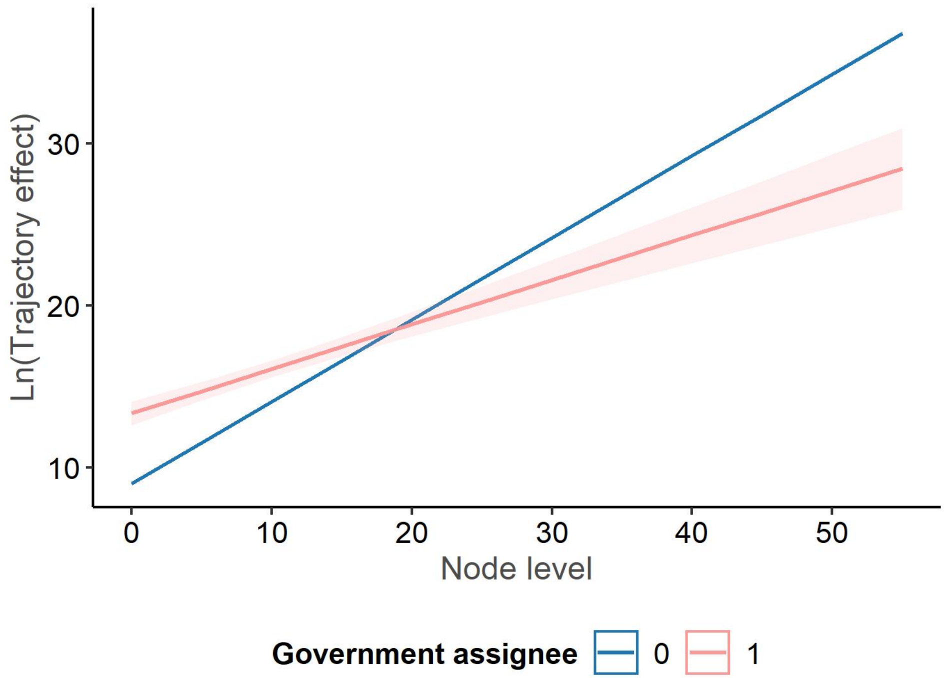
Federal agencies or state departments patents have, on average, a trajectory effect 868.4% higher than other patents

The effect is stronger in early phases of development

Government grants



Government inventions



Robustness checks

- Quasi-experimental designs (to control for *selection bias*):
  - **1-1 matching** without replacement: propensity score matching on technology classes (3-digits CPC) and time (timing)
  - **Instrumental variable**: predicted number of government-funded patents in CPC classes

- Other robustness checks:
  - Other indicators of trajectory effect: longest path length
  - Time effect: forward trajectory effect
  - Indirect government funding
  - Sample composition: only WIPO (2019) patents and patents after 1980
  - Additional controls: worldwide university, backward citations, and average growth rate of CPC classes (lagged)

- Patent relevance: tests on the effects of key variables on standard indicators (number of citations) give very different results (generally negative effects!).

Conclusions

US government grants and, especially, patents filed by federal agencies and government departments had profound effects on AI innovation.

Their impact was stronger in early phase of technological development, while it weakened over time to leave room to privately funded research.

Main contributions:

- Novel and original evidence on the influence of government funding on the direction of technical change.
- Large-scale development and application of a novel indicator to measure the effect of innovation on follow-on technological change.
- Contribution to the emergent literature on the economics of AI: novel quantitative evidence of key financing patterns that have supported the development of these technologies over the last thirty years…

Thank you!

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USPTO patents in AI

We select 114,670 USPTO patents connected through directed and undirected citations that respect the time flow

Technology name	Number of patents	%
Electrical engineering - Computer technology	74192	64.72
Instruments - Control	8513	7.43
Mechanical engineering - Transport	5378	4.69
Instruments - Measurement	4346	3.79
Electrical engineering - Audio-visual technology	4306	3.76
Instruments - Medical technology	3587	3.13
Electrical engineering - Digital communication	2804	2.45
Electrical engineering - Telecommunications	2110	1.84
Electrical engineering - IT methods for management	1808	1.58
Mechanical engineering - Mechanical elements	1094	0.95

Main technologies in AI patents

Assignee	Number of patents	%
International Business Machines Corporation	6710	5.85
Microsoft Corporation	3927	3.42
Google Inc.	3094	2.70
Canon Kabushiki Kaisha	1834	1.60
Samsung Electronics Co., Ltd.	1655	1.44
Sony Corporation	1602	1.40
AT&T Corporation	1191	1.04
Amazon Technologies, Inc.	1169	1.02
Xerox Corporation	1087	0.95
Fujitsu Limited	1068	0.93

Main assignees of AI patents

Government funded patents in AI: the role of the Department of Defense

Assignee	Number of patents	%
Secretary of the Navy	370	39.83
National Aeronautics and Space Administration	153	16.47
Secretary of the Army	109	11.73
Secretary of the Air Force	106	11.41
Department of Energy	33	3.55
National Security Agency	29	3.12
Department of Health and Human Services	29	3.12
United States Postal Service	22	2.37
Lawrence Livermore National Security	19	2.05
Department of Commerce	10	1.08

929 government assignee patents

Federal agency	Number of patents	%
Department of Defense	1670	46.43
United States Government	703	19.54
Department of Health and Human Services	627	17.43
National Science Foundation	478	13.29
Department of Energy	462	12.84
National Aeronautics and Space Administration	166	4.61
Small Business Administration	42	1.17
Department of Transportation	36	1.00
Department of Commerce	36	1.00
Department of Homeland Security	35	0.97

3597 government interest patents