Innovation Adaptation in Knowledge Space: Evidence from Patent Eligibility Shocks

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Motivation: Adjusting Innovation Choices in a Dynamic Environment

Innovation is inherently dynamic:

- technological opportunities emerge, evolve, and become more or less attractive over time
- the return to an innovation project can change as economic conditions evolve

Innovators continuously adjust their innovation choices:

$$\begin{tikzcd} \text{Choose innovation projects} \arrow[r] & \text{Environment changes} \arrow[r] & \text{Returns to chosen project change} \arrow[ll, bend right] \end{tikzcd}$$

The quality of adaptation depends on whether innovators have valuable alternative innovation projects.

Research Question: *Why do some innovators have access to more valuable alternative innovation projects than others?*

Characterizing the Knowledge Space

To study the accessibility of alternative innovation projects, we need to characterize their **relative positions** in an underlying knowledge space.

- Following Schumpeter (1964) and Weitzman (1998), innovations can be viewed as recombinations of existing knowledge components. An innovation project can therefore be represented by the knowledge components it combines:

$$x = \{k_1, k_2, \ldots, k_n\}$$

- We measure the proximity between two knowledge components based on how frequently they are combined relative to their overall use in innovation (Jaffe, 1986; Alstott et al., 2017):

$$\rho_{ij} = Proximity(k_i, k_j)$$

Reframed Research Question: *Why do some innovators have alternative innovation projects nearby than others?*

Alice: An Adverse Shock to the Knowledge Space

The Alice Decision (2014): The U.S. Supreme Court tightened patent eligibility for abstract ideas, disproportionately affecting software and business methods (Chien and Wu, 2018) ◂ Exogeneity

Mapping to the Knowledge Space:

- Knowledge component k_i = technology class i
  $\Rightarrow$ Patent $p = \{k_1, k_2, \ldots, k_n\}$
- $Exposure_p = \sum_i w_i Exposure_i$ ◂ Exposure

Special Patterns of the Alice Shock:

- Patent grants in high-exposure technologies recovered after the initial disruption ◂ Trend
- Inventions combining multiple technology classes are less likely to receive Alice-related rejections ◂ Proportions

Affected innovators may find alternatives through relatively small adjustments, recombining across technology classes without leaving the affected field altogether.

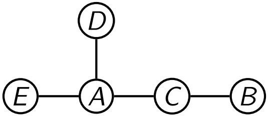
$$A \rightarrow AB \dashrightarrow B$$

Knowledge Proximity and Local Adaptation

How easily can innovators find nearby combinations around a focal technology?

$\Rightarrow$ It depends on the local structure of the technology space

Technology Network:



More proximate technology classes $\Rightarrow$ Greater recombination opportunities

Measure Recombination Opportunities:

1. proximity between knowledge components: $\rho_{ij} = \frac{N_{ij}}{\sqrt{N_i N_j}}$
   where N_i is number of historical patents with technology class i
2. Recombination opportunities for technology i: $RO_i = \sum_{j \neq i} \rho_{ij}$

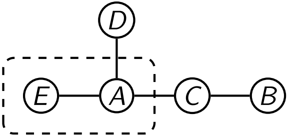
◂ Distribution

Firm Boundaries and Recombination Capacity

Whether are combinative technologies available to innovators?

$\Rightarrow$ It depends on firm technological boundaries which are defined by firms' innovation experience

Firm f's Patent Portfolio K_f:



Firm technological boundary

Measure Recombination Capacity for Firm i:

1. Recombination opportunities for firm f and technology i:
   $RO_{fi} = \sum_{j \neq i} \rho_{ij} \mathbb{I}(j \in K_f)$
2. Recombination Capacity for firm f: $RC_f = \sum_i w_{fi} RO_{fi}$
   where w_{fi} is the proportion of patents in technology i

Distribution

Cross-Technology Recombination after Alice

Innovators respond to Alice by recombining with additional technology classes.

- **Sample:** US patent applications filed in 2006–2023
- **Treatment:** Alice exposure of the primary technology class

Continuous Treatment:

	Num. of Classes		Exposure Reduction	
	(1)	(2)	(3)	(4)
Class Exposure × Post	0.523***	0.530***	0.191***	0.193***
	(7.30)	(5.92)	(9.82)	(7.36)
Primary Class FE	Yes	Yes	Yes	Yes
Filing Year FE	Yes	Yes	Yes	Yes
Clustering	Primary Class	Primary Class	Primary Class	Primary Class
Pseudo/Adj. R^2	0.0325	0.0327	0.4477	0.5112
Num. of Observations	6586138	4772492	6586138	4772492
Sample	Pub Apps	Grants	Pub Apps	Grants
Model	PPML	PPML	OLS	OLS

Cross-Technology Recombination after Alice

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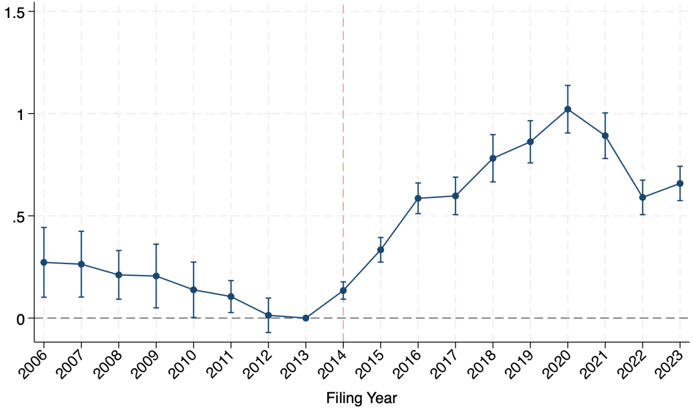
Dynamic Effect on Num. of Classes:



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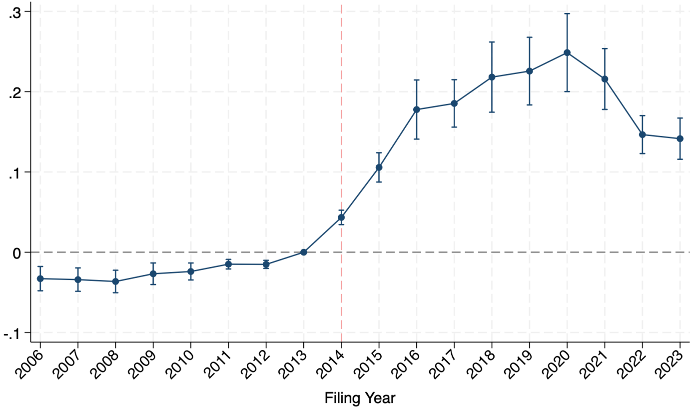
Dynamic Effect on Exposure Reduction:



Cross-Technology Recombination after Alice

Innovators respond to Alice by recombining with additional technology classes.

- **Sample:** US patent applications filed in 2006–2023
- **Treatment:** Alice exposure of the primary technology class

Discrete Version:

	Num. of Classes		Exposure Reduction	
	(1)	(2)	(3)	(4)
Med. Exposure × Post	0.0570***	0.0589***	0.000521**	0.000540**
	(2.85)	(3.27)	(2.04)	(2.53)
High Exposure × Post	0.137***	0.138***	0.0416***	0.0397**
	(3.36)	(3.33)	(2.65)	(2.40)
Primary Class FE	Yes	Yes	Yes	Yes
Filing Year FE	Yes	Yes	Yes	Yes
Clustering	Primary Class	Primary Class	Primary Class	Primary Class
Pseudo/Adj. R^2	0.0326	0.0328	0.4321	0.4968
Num. of Observations	6586138	4772492	6586138	4772492
Sample	Pub Apps	Grants	Pub Apps	Grants
Model	PPML	PPML	OLS	OLS

Recombination Opportunities Shape Adaptive Responses

Conditional on Alice exposure, innovators expand cross-technology combination more when recombination opportunities are greater.

- **Sample:** US patent applications filed in 2006–2023
- **Treatment:** Alice exposure (heterogeneous by recombination opportunities)

Heterogeneous Effect by Recombination Opportunities:

	Num. of Classes		Exposure Reduction	
	(1)	(2)	(3)	(4)
Class Exposure × Post	0.542***	0.545***	0.197***	0.199***
	(9.59)	(7.22)	(24.36)	(18.10)
Recombination Opportunities × Post	-0.0269***	-0.0283***	-0.000512*	-0.000675**
	(-2.74)	(-2.75)	(-1.67)	(-2.02)
Class Exposure × Recombination Opportunities × Post	0.454**	0.521***	0.0719***	0.0827***
	(2.33)	(2.62)	(2.88)	(3.27)
Primary Class FE	Yes	Yes	Yes	Yes
Filing Year FE	Yes	Yes	Yes	Yes
Clustering	Primary Class	Primary Class	Primary Class	Primary Class
Pseudo/Adj. R^2	0.0326	0.0328	0.4479	0.5114
Num. of Observations	6586138	4772492	6586138	4772492
Sample	Pub Apps	Grants	Pub Apps	Grants
Model	PPML	PPML	OLS	OLS

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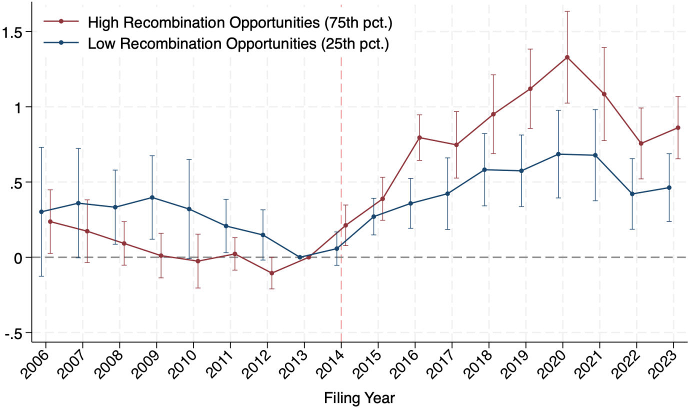
- **Treatment:** Alice exposure (heterogeneous by recombination opportunities)

Dynamic Effect: High vs. Low Recombination Opportunities:



Recombination Opportunities Shape Adaptive Responses

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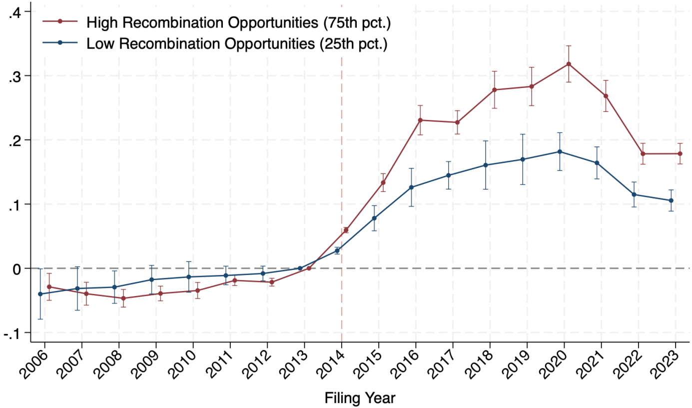
- **Treatment:** Alice exposure (heterogeneous by recombination opportunities)

Event Study (Exposure Reduction):



Recombination Opportunities Shape Adaptive Responses

Conditional on Alice exposure, innovators expand cross-technology combination more when recombination opportunities are greater.

- **Sample:** US patent applications filed in 2006–2023
- **Treatment:** Alice exposure (heterogeneous by recombination opportunities)

Discrete Version:

	Num. of Classes		Exposure Reduction	
	(1)	(2)	(3)	(4)
Med. Exposure × Post	0.0560***	0.0602***	0.000554**	0.000561***
	(3.12)	(3.61)	(2.26)	(2.62)
High Exposure × Post	0.157***	0.162***	0.0545***	0.0540***
	(4.48)	(4.68)	(4.81)	(4.52)
Recombination Opportunities × Post	-0.0273***	-0.0294***	0.0000354**	0.0000412***
	(-3.31)	(-3.29)	(2.24)	(2.59)
Med. Exposure × Recombination Opportunities × Post	0.0167	0.0152	-0.000209	-0.000151
	(0.70)	(0.79)	(-1.02)	(-0.85)
High Exposure × Recombination Opportunities × Post	0.0939**	0.0981**	0.0369***	0.0369***
	(2.36)	(2.40)	(3.37)	(3.36)
Primary Class FE	Yes	Yes	Yes	Yes
Filing Year FE	Yes	Yes	Yes	Yes
Clustering	Primary Class	Primary Class	Primary Class	Primary Class
Pseudo/Adj. R^2	0.0326	0.0328	0.4321	0.5142
Num. of Observations	6586138	4772492	6586138	4772492
Sample	Pub Apps	Grants	Pub Apps	Grants
Model	PPML	PPML	OLS	OLS

Firms' Recombination Capacity and Patenting Activities

Firms with greater recombination capacity are better able to sustain patenting in Alice-exposed technologies.

- **Sample:** Public firms with pre-Alice patent portfolios
- **Treatment:** Number of Alice-exposed patents in firms' pre-Alice portfolios

	Number of Patent Applications					
	Total		High-Exposure Tech		Low-Exposure Tech	
	(1)	(2)	(3)	(4)	(5)	(6)
Firm Exposure × Post	-0.0184**	-0.0908	-0.0283***	-0.290***	-0.00141	-0.0616
	(-2.30)	(-1.43)	(-3.79)	(-3.34)	(-0.13)	(-0.67)
Recombination Capacity × Post		0.0558		0.0923		0.0300
		(1.02)		(1.18)		(0.50)
Firm Exposure × Recombination Capacity × Post		0.0244		0.0888***		0.0216
		(1.14)		(3.15)		(0.69)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry × Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Clustering	Firm	Firm	Firm	Firm	Firm	Firm
Pseudo R^2	0.9636	0.9636	0.8853	0.8868	0.9568	0.9569
Num. of Observations	29998	29998	16234	16234	26365	26365

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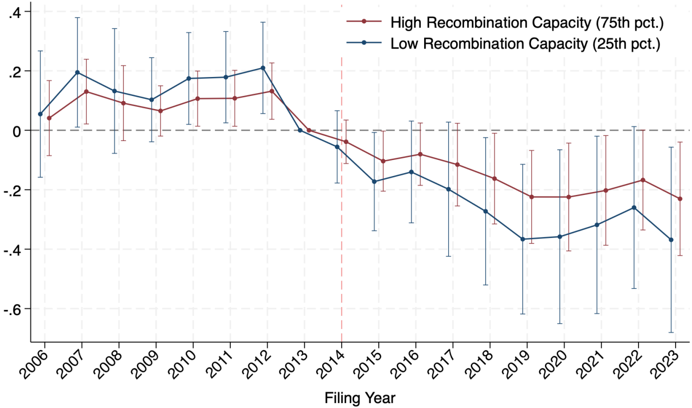
Dynamic Effect on Patenting in High-Exposure Technologies:



Firms' Recombination Capacity and Patenting Activities

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- **Sample:** Public firms with pre-Alice patent portfolios
- **Treatment:** Number of Alice-exposed patents in firms' pre-Alice portfolios

Recombination Potential without Boundaries:

	Number of Patent Applications		
	Total	High-Exposure Tech	Low-Exposure Tech
	(1)	(2)	(3)
Firm Exposure × Post	-0.0184**	-0.0239**	0.000414
	(-2.41)	(-2.24)	(0.05)
Recombination Potential × Post	0.0850	-0.00951	0.0431
	(0.83)	(-0.07)	(0.41)
Firm Exposure × Recombination Potential × Post	-0.0239	-0.0386	0.0166
	(-0.80)	(-0.97)	(0.41)
Firm Controls	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Industry × Year FE	Yes	Yes	Yes
Clustering	Firm	Firm	Firm
Pseudo R^2	0.9636	0.8854	0.9569
Num. of Observations	29998	16234	26365

Firms' Recombination Capacity and Performance

Firms more exposed to Alice experience larger declines in performance, while recombination capacity mitigates these losses.

- **Sample:** Public firms with pre-Alice patent portfolios
- **Treatment:** Number of Alice-exposed patents in firms' pre-Alice portfolios

	log(Sales)		Sales/Employees		Log(MVE)	
	(1)	(2)	(3)	(4)	(5)	(6)
Firm Exposure × Post	-0.0102	-0.0853**	-0.949	-41.02**	-0.0171	-0.160***
	(-1.14)	(-2.56)	(-0.38)	(-2.04)	(-1.32)	(-3.53)
Recombination Capacity × Post		0.0161		34.81***		0.0630***
		(1.00)		(2.98)		(3.22)
Firm Exposure × Recombination Capacity × Post		0.0268**		12.23*		0.0486***
		(2.36)		(1.90)		(3.06)
Firm Controls	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry × Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Clustering	Firm	Firm	Firm	Firm	Firm	Firm
Adj. R^2	0.9606	0.9606	0.6955	0.6958	0.9285	0.9286
Num. of Observations	29655	29655	29274	29274	30666	30666

Additional Evidence on Knowledge Recombination and Adaptation

Beyond Innovation Outcomes: Changes in the Innovation Process

- More exposed technologies involve more diverse inventor teams Evidence
- More exposed technologies rely on more diverse backward citations Evidence

Alternative Definition of Knowledge Components: Individual Patents

- Exposed patents are cited in the development of less-exposed patents Evidence
- Patent owners use continuation-in-part filings to reduce exposure of modified inventions Evidence

Firm Adaptation: Changes in Technological Boundaries

- Firms with higher recombination capacity increase exploitation of existing technologies
- Firms with higher recombination capacity expand into new technologies Evidence

Conclusion

We develop a **knowledge-space** framework to understand how innovators adapt to dynamic innovation environment.

Adaptation depends on:

- **technological proximity:** the availability of nearby knowledge components in the knowledge space
- **organizational boundaries:** access to existing knowledge within firms

Using **Alice** as a laboratory, we show that:

- Innovators adapt through cross-technology recombination, with stronger responses when more alternative technologies are available in the technology space.
- Firms with greater recombination capacity are more resilient to the shock, sustaining innovation and mitigating performance losses.

References

Alstott, Jeff, Giorgio Triulzi, Bowen Yan, and Jianxi Luo, "Mapping technology space by normalizing patent networks," *Scientometrics*, 2017, *110* (1), 443–479.

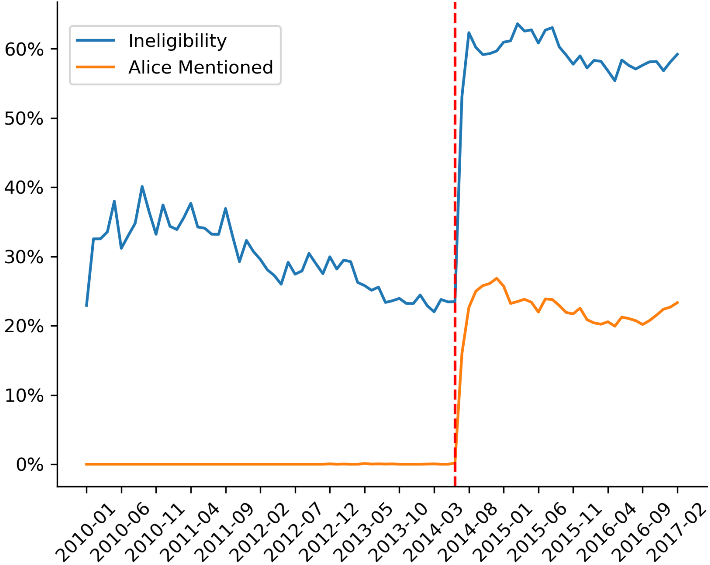
Chien, Colleen V and Jiun Ying Wu, "Decoding patentable subject matter," *Patently-O Patent Law Journal*, 2018, *1.*

Jaffe, Adam B, "Technological opportunity and spillovers of R&D: evidence from firms' patents, profits and market value," 1986.

Schumpeter, Joseph Alois, "Business Cycles: A theoretical, historical and statistical analysis of the Capitalist process, 1939," *Acessado em*, 1964, *4.*

Weitzman, Martin L, "Recombinant growth," *The quarterly journal of economics*, 1998, *113* (2), 331–360.

Immediate Increase in Patent Examination Rejections (High-Exposure Technologies)



Return

CPC Subclasses with High Alice Exposure

CPC Subclass	Short Description	Exposure (%)	
		OLS	GLMM
G06Q	ICT for administrative or business purposes	28.14	34.36
G07F	Coin or payment-operated apparatus	25.25	27.85
G16B	Bioinformatics and computational genomics	18.43	25.91
A63F	Games and amusement devices	20.51	24.81
G16C	Computational chemistry and molecular informatics	14.68	23.08
G07B	Ticketing, fare collection, and access control	18.07	18.06
G09B	Educational or demonstration apparatus	13.16	15.75
G16Z	ICT applied to specific fields	5.63	12.98
G01W	Meteorology-related measurement and forecasting	10.83	10.61
G07G	Registering cash registers, point-of-sale systems, and related devices	3.64	9.77
C12Q	Measuring or testing processes involving enzymes, nucleic acids, or microorganisms	4.87	6.28
G09C	Cryptography and secure communication	3.23	6.10
G01V	Geophysics; detection of underground structures or resources	4.87	5.82
G16H	Healthcare informatics	5.64	5.81
G01C	Measuring distances, navigation, and positioning	4.70	5.65
G10L	Speech analysis, recognition, and processing	4.50	5.42
G07C	Time or attendance registers; time recording devices	3.77	5.33

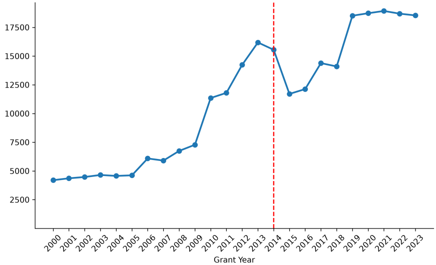
Return

Weights between Primary and Secondary Classes

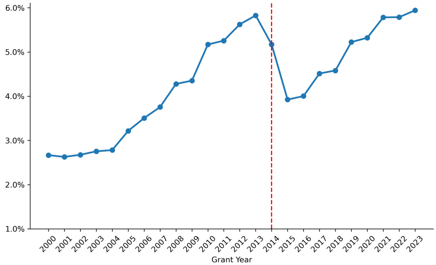
$N_{\text{subclasses}}$	$N_{\text{applications}}$ (Share)	OLS Estimates (%)		GLMM Weights (%)	
		Primary	Secondary	Primary	Secondary
1	313,143 (45.18)	118.91	–	100.00	0.00
2	222,836 (32.15)	65.93	24.67	70.28	29.72
3	102,798 (14.83)	53.61	31.07	54.18	45.82
4	38,470 (5.55)	43.12	40.22	44.08	55.92
5	12,883 (1.86)	29.12	58.63	37.16	62.84
6	4,336 (0.63)	22.22	88.63	32.11	67.89
7+	2,870 (0.41)	-3.49	51.33	28.27	71.73

Return

Trend of Patent Grants in High-Exposure Technologies



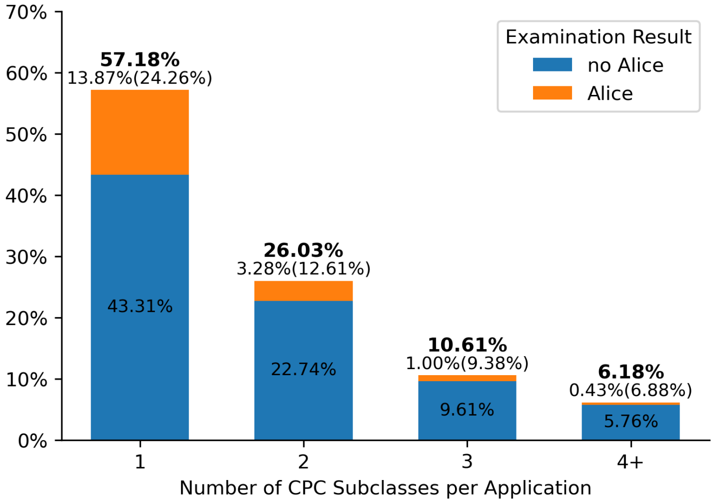
(a) Number of Patent Grants



(b) Share of Patent Grants

Return

Cross-Class Recombination and Patent Exposure



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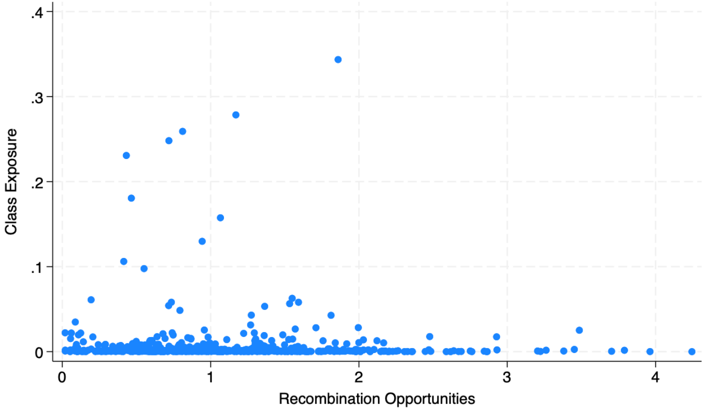
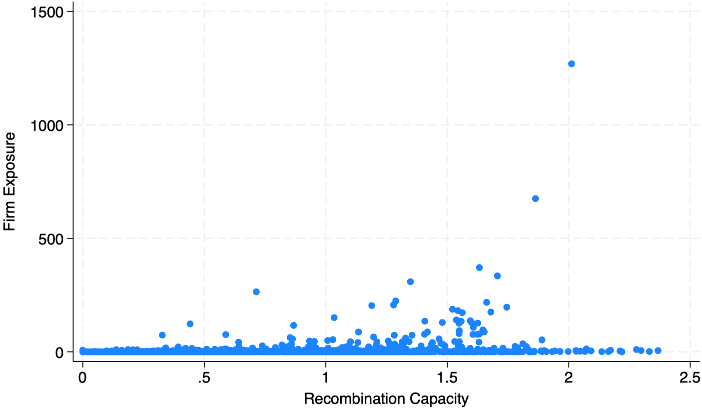
Distribution of Recombination Opportunities



◂ Return

Distribution of Recombination Capacity



◂ Return

Changes of Inventor Teams

	Team Knowledge Breadth		Team Knowledge Dispersion		Member Knowledge Distance	
	(1)	(2)	(3)	(4)	(5)	(6)
Class Exposure × Post	0.189*	0.220**	0.0829**	0.0954***	0.0832***	0.0942***
	(1.88)	(2.24)	(2.32)	(5.91)	(2.59)	(6.78)
Recombination Capacity × Post		-0.000840		-0.00602***		0.000327
		(-0.07)		(-2.90)		(0.26)
Class Exposure × Recombination Capacity × Post		0.325		0.162*		0.123***
		(1.10)		(1.75)		(3.23)
Primary Class FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Clustering	Primary Class	Primary Class	Primary Class	Primary Class	Primary Class	Primary Class
Pseudo/Adj. R^2	0.0760	0.0760	0.0364	0.0365	0.0587	0.0588
Num. of Observations	6586135	6586135	5801352	5801352	3760282	3760282
Model	PPML	PPML	OLS	OLS	OLS	OLS

Return

Changes of Backward Citations

	Citation Breadth		Citation Dispersion	
	(1)	(2)	(3)	(4)
Class Exposure × Post	0.129	0.129**	0.00331	0.0157
	(1.63)	(2.57)	(0.09)	(0.97)
Recombination Opportunities × Post		-0.0359***		-0.0172***
		(-3.64)		(-4.40)
Class Exposure × Recombination Opportunities × Post		0.403**		0.217***
		(2.46)		(3.23)
Primary Class FE	Yes	Yes	Yes	Yes
Filing Year FE	Yes	Yes	Yes	Yes
Clustering	Primary Class	Primary Class	Primary Class	Primary Class
Pseudo/Adj. R^2	0.0890	0.0892	0.1070	0.1077
Num. of Observations	4511111	4511111	4511111	4511111
Model	PPML	PPML	OLS	OLS

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Changes of Backward Citations

Panel A: Comparison of Cited and Citing Patents				
	Num. of Classes Increase	Num. of New Classes	I(Different Primary Classes)	Exposure Reduction
Class Exposure × Post	0.449***	0.316***	0.128***	0.110***
	(13.91)	(12.20)	(8.52)	(53.84)
Cited Patent FE	Yes	Yes	Yes	Yes
Citation Lag FE	Yes	Yes	Yes	Yes
Clustering	Cited Patent	Cited Patent	Cited Patent	Cited Patent
Pseudo/Adj. R^2	0.4514	0.1929	0.1415	0.5748
Num. of Observations	21710221	21295412	20791074	21710221
Model	OLS	PPML	PPML	OLS
Panel B: Exposure Distribution of Backward Citations				
	(1)	(2)	(3)	(4)
	Mean	Median	Mean of Top 25%	Mean of Bottom 25%
Class Exposure × Post	-0.0413***	-0.0490***	-0.0314***	-0.0395***
	(-31.10)	(-24.06)	(-20.36)	(-34.72)
Cited Patent FE	Yes	Yes	Yes	Yes
Citation Lag FE	Yes	Yes	Yes	Yes
Clustering	Cited Patent	Cited Patent	Cited Patent	Cited Patent
Pseudo/Adj. R^2	0.8380	0.7669	0.8071	0.7454
Num. of Observations	21710221	21710221	21710221	21710221
Model	OLS	OLS	OLS	OLS

Return

Cited-Citing Patent Pairs

Panel A: Comparison of Cited and Citing Patents				
	Num. of Classes Increase	Num. of New Classes	I(Different Primary Classes)	Exposure Reduction
Class Exposure × Post	0.449***	0.316***	0.128***	0.110***
	(13.91)	(12.20)	(8.52)	(53.84)
Cited Patent FE	Yes	Yes	Yes	Yes
Citation Lag FE	Yes	Yes	Yes	Yes
Clustering	Cited Patent	Cited Patent	Cited Patent	Cited Patent
Pseudo/Adj. R^2	0.4514	0.1929	0.1415	0.5748
Num. of Observations	21710221	21295412	20791074	21710221
Model	OLS	PPML	PPML	OLS
Panel B: Exposure Distribution of Backward Citations				
	(1)	(2)	(3)	(4)
	Mean	Median	Mean of Top 25%	Mean of Bottom 25%
Class Exposure × Post	-0.0413***	-0.0490***	-0.0314***	-0.0395***
	(-31.10)	(-24.06)	(-20.36)	(-34.72)
Cited Patent FE	Yes	Yes	Yes	Yes
Citation Lag FE	Yes	Yes	Yes	Yes
Clustering	Cited Patent	Cited Patent	Cited Patent	Cited Patent
Pseudo/Adj. R^2	0.8380	0.7669	0.8071	0.7454
Num. of Observations	21710221	21710221	21710221	21710221
Model	OLS	OLS	OLS	OLS

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Continuation Children

	Continuation (rewrite claims)		Continuation-in-Part (add new matters)	
Panel A: Number of Continuation Children				
	(1) in 3 years	(2) in 5 years	(3) in 3 years	(4) in 5 years
Post	0.0288	0.0445**	-0.000256	-0.00741
	(1.47)	(2.45)	(-0.01)	(-0.18)
Class Exposure×Post	0.345	-0.464*	0.733**	0.588**
	(1.25)	(-1.86)	(2.49)	(2.06)
Pending Duration	-0.730***	-0.257***	-0.104***	-0.0605***
	(-21.76)	(-20.05)	(-5.60)	(-3.85)
Primary Class FE	Yes	Yes	Yes	Yes
Filing Year FE	Yes	Yes	Yes	Yes
Number of Obs.	1593744	1594940	1593012	1593793
Panel B: Expand Number of Technology Classes by Continuity				
	Continuation (rewrite claims)		Continuation-in-Part (add new matters)	
	(1) in 3 years	(2) in 5 years	(3) in 3 years	(4) in 5 years
Post	-0.658***	-0.820***	-0.161***	-0.220***
	(-4.22)	(-6.03)	(-3.30)	(-4.68)
Post × Class Exposure	0.00965	-1.218	1.075***	0.898**
	(0.01)	(-1.30)	(2.92)	(2.42)
Pending Duration	-0.154**	-0.0553	-0.0429***	-0.000319
	(-2.50)	(-1.15)	(-2.59)	(-0.02)
Primary Class FE	Yes	Yes	Yes	Yes
Filing Year FE	Yes	Yes	Yes	Yes
Number of Obs.	1289778	1385673	1582891	1585638

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Changes of Firm Technological Boundaries

	Technology Scope		Existing Technology Reuse		New Technology Entry	
	(1)	(2)	(3)	(4)	(5)	(6)
Firm Exposure × Post	-0.00726**	-0.0869**	-0.0134***	-0.109***	-0.0181**	-0.101**
	(-1.96)	(-2.49)	(-3.03)	(-2.73)	(-2.23)	(-2.11)
Recombination Capacity × Post		-0.0393*		-0.0689***		-0.110***
		(-1.84)		(-2.72)		(-5.32)
Firm Exposure × Recombination Capacity × Post		0.0301***		0.0368***		0.0349**
		(2.67)		(2.88)		(2.17)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry × Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Clustering	Firm	Firm	Firm	Firm	Firm	Firm
Pseudo R^2	0.8772	0.8775	0.8831	0.8836	0.5557	0.5570
Num. of Observations	29998	29998	28511	28511	28775	28775

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