Team-Specific Capital and Innovation*

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June 2015

Abstract

We show that the accumulation of team-specific capital is important for the typical patent inventor's lifecycle earnings and productivity, much like firm-specific capital is crucial for the typical worker. Using administrative tax and patent data for the population of US patent inventors from 1996 to 2012 and employing a difference-in-differences research design based on the premature deaths of 4,714 inventors, we establish that an inventor's premature death causes a large and long-lasting decline in their co-inventor's earnings and citation-weighted patents (-4% and - 15% after 8 years, respectively). We rule out firm disruption, network effects and top-down spillovers as primary drivers of this result. Consistent with the team-specific capital interpretation, the effect is larger for more closely-knit teams and primarily applies to co-invention activities with the deceased.

*The opinions expressed in this paper are those of the authors alone and do not necessarily reflect the views of the Internal Revenue Service or the U.S. Treasury Department. We thank Philippe Aghion, David Autor, Pierre Azoulay, Kirill Borusyak, Gary Chamberlain, Raj Chetty, Iain Cockburn, Riccardo Crescenzi, Max Eber, Itzik Faldon, Andy Garin, Sid George, Duncan Gilchrist, Ed Glaeser, Paul Goldsmith-Pinkham, Ben Golub, Adam Guren, Nathan Hendren, Simon Jaeger, Larry Katz, Bill Kerr, Josh Lerner, Jonathan Libgober, Filippo Mezzanotti, Alexandra Roulet, Andrei Shleifer, John Van Reenen, Martin Watzinger, Heidi Williams and seminar participants at the NBER Productivity Seminar and Harvard Labor Lunch for thoughtful discussions and comments. Jaravel gratefully acknowledges financial support from the HBS doctoral office.

I Introduction

Teamwork has become an essential feature of modern economies and knowledge production (Seaborn, 1979, Wuchty et al., 2007, Jones, 2010, and Crescenzi et al., 2015). We investigate empirically the importance of *team-specific capital* for the compensation and patent production of inventors, using administrative tax and patent data for the population of US patent inventors from 1996 to 2012. While general human capital augments productivity at all firms (Becker, 1975), and while firm-specific capital augments productivity with any existing or future collaborators within the firm (Topel, 1991), team-specific capital makes an inventor more productive with their existing co-inventors. If the collaboration between two patent inventors were to exogenously end, would this have a significant and long-lasting impact on the career, compensation and productivity of these inventors? In other words, is the accumulation of team-specific capital an important ingredient of the typical inventor's lifecycle earnings and productivity, much like firm-specific capital is crucial for the typical worker?

We provide causal estimates of what the typical inventor would lose, in terms of labor earnings, total earnings and patent production, if a collaboration with one of their co-inventors were to end. Using a detailed merged dataset of United States Patent and Trademark Office (USPTO) patents data and IRS administrative tax data, we use the premature deaths of 4,714 inventors, defined as deaths that occur before the age of 60, as a source of exogenous variation in collaborative networks. The causal effect is identified in a difference-in-differences research design, using a control group of patent inventors whose co-inventors did not pass away but who were otherwise similar to the inventors who experienced the premature death of a co-inventor. We find that ending a collaboration causes a large and long-lasting decline in an inventor's labor earnings (- 3.8% after 8 years), total earnings (- 4% after 8 years) and citation-weighted patents (- 15% after 8 years). This evidence implies that the continuation of collaborative relationships has substantial specific value for the typical inventor, close to half of the returns to one year of schooling (Mincer, 1973). It rejects the alternative hypothesis that continued collaborations are not a key ingredient in an inventor's earnings function and patent production function beyond short-term disruption of ongoing work.

To establish team-specific capital as the primary explanatory mechanism,[1] we show that the gradual decline in earnings and citation-weighted patents following the premature death of a co-

[1] Team-specific capital encompasses skills, experiences and knowledge that are useful only in the context of a specific collaborative relationship. It can be conceptualized as the idiosyncratic match quality between co-inventors in a team. A higher match quality means that the team is more productive, which improves each inventor's ability to produce valuable innovations with these specific co-inventors.

inventor is driven by the fact that the inventor lost a partner with whom they were collaborating extensively, which made additional co-inventions impossible. We do so in four steps. First, we rule out alternative explanatory mechanisms that are not specific to the team. We establish that the effect does not stem from the disruption of the firm or from network effects by estimating the causal effect of an inventor's death on his coworkers and on inventors that are two nodes away from the deceased in the co-inventor network.[2] Second, we show that the effect is not driven by top-down spillovers from unusually high-achieving deceased inventors (e.g. as in Azoulay et al., 2010, and Oettl, 2012). Third, we demonstrate that the intensity of the collaboration between an inventor and their deceased co-inventor prior to death is an important predictor of the magnitude of the effect. Fourth, we document that the effect of co-inventor death on an inventor's patents is much smaller when patents that were co-invented with the deceased are not taken into account in the difference-in-differences analysis, i.e. the effect primarily applies to co-invention activities with the deceased. We also show that team-specific capital matters in all technology categories, at various levels of the distribution of patent quality, and spans firm and geographic boundaries. In Section IV, we discuss whether other mechanisms could be consistent with the evidence.

Beyond establishing the first-order importance of team-specific capital, the paper makes two additional contributions. First, we present new descriptive statistics on collaboration patterns and the composition of teams. We find that assortative matching is true only up to a point: there is wide variation in the relative earnings and age of co-inventors. Second, we introduce a novel specification to estimate the causal effect of an individual's premature death, which includes all leads and lags around co-inventor death in both the treatment and control groups. This specification is robust to mechanical statistical patterns induced by the construction of the sample, which have not been addressed in the existing literature and which we show result in substantial biases of the estimates of interest.[3]

Our work relates to several strands of literature. The use of premature deaths as a source of

[2]In addition to ruling out important alternative mechanisms that could explain our finding, this analysis yields new insights about substitution and complementarity patterns between inventors in the innovation production function. See Section IV for a complete discussion.

[3]It is not sufficient to control for age, year and individual fixed effects in the difference-in-differences estimator, because these fixed effects do not fully account for the trends in lifecycle earnings and patents around the year of co-inventor death. Intuitively, an inventor must necessarily have invented a patent before the year of death of their co-inventor and is more likely to have been employed at that time, even conditional on a large set of fixed effects. We show that this results in a substantial bias in the estimate of the causal effect for several of the outcomes we study in this paper. Including a full set of leads and lags around co-inventor death for both treated and control inventors addresses this problem. This solution is an application of the standard difference-in-differences estimator, where treatment occurs at only one point in time, to our setting, where co-inventor deaths are scattered across years. Similar considerations apply when estimating heterogeneity in the treatment effect. See Section III and Appendix D for more details and for a comparison with the existing literature using premature death research designs.

identification is becoming increasingly common (Jones and Olken, 2005, Bennedsen et al., 2007, Azoulay et al., 2010, Nguyen and Nielsen, 2010, Oettl, 2012, Becker and Hvide, 2013, Fadlon and Nielsen, 2014, Isen, 2015). Several papers have investigated peer effects in specific areas of science (Azoulay et al., 2010, Borjas and Doran, 2012, 2014, Oettl, 2012, Waldinger, 2010, 2012). In contrast, our paper studies peer effects among patent inventors in all technology classes, using both earnings and patent data (Moser et al., 2014, study German emigres' effects on US chemical patents). Moreover, there is a growing literature on the role of teams for innovation (e.g. De Dreu, 2005, Jones, 2009, Agrawal et al., 2013, Alexander and van Knippenberg, 2014) and on the theory of knowledge spillovers across inventors (Stein, 2008, Lucas and Moll, 2014). As discussed in Section IV, our results on spillover effects between inventors who are two nodes away from each other in the co-inventor network provides a test of competing models of strategic interactions in networks (Jackson and Wolinsky, 1996, Bramoulle et al., 2014). Finally, this paper is part of a nascent literature using administrative data to describe the careers of patent inventors (Toivanen and Vaananen, 2012, Dorner et al., 2015, Depalo and Di Addario, 2015, Bell et al., 2015).

This paper has important implications for innovation policy. Our findings suggest that investing in improving the match technology between inventors could lead to substantial productivity gains. Furthermore, our results indicate that research teams are an important vehicle for knowledge transmission and such team collaborations affect the productivity of team members outside of their joint projects (even though, as noted earlier, the effect is larger for co-invention activities). Teamwork improves inventors' productivity and increases their incomes, which generates additional tax revenues and creates large fiscal externalities.

The remainder of the paper is organized as follows. In Section II, we present the dataset and novel descriptive statistics on the composition of teams. In Section III, we describe the research design and present the estimates of the causal effect of the premature death of a co-inventor on an inventor's compensation and patents. In Section IV, we distinguish between various mechanisms. Section V concludes. Several robustness checks, heterogeneity results and empirical estimation details are deferred to the Appendices. Appendix A reports additional summary statistics and tests for balance between treated and control groups. Appendix B presents robustness checks on the causal effect of co-inventor death. Appendix C conducts additional tests for heterogeneity in the effect of co-inventor death. Appendix D provides additional details on our econometric framework. Appendix E describes the construction of the dataset and reports additional summary statistics on the composition of inventor teams.

II Data and Descriptive Statistics

II.A Data Construction

We use a merged dataset of United States Patent and Trademark Office (USPTO) patents data and Treasury administrative tax files as in Bell et al. (2015). The patent data are extracted from the weekly text and XML files of patent grant recordations hosted by Google. The raw files contain the full text of about 5 million patents granted from 1976 to today, extracted from the USPTO internal databases in weekly increments.

Administrative data on the universe of U.S. taxpayers is sourced from Treasury administrative tax files. We extract information on inventors' city and state of residence, wages, employer ID, adjusted gross income, as well as current citizenship status and gender from Social Security records. Most data are available starting in 1996, however wages and employer ID are available only starting in 1999, which marks the beginning of W-2 reporting. Inventors from the USPTO patent data are matched to individual taxpayers using information on name, city and state of residence (Appendix A describes the iterative stages of the match algorithm). The match rate is over 85% and the matched and unmatched inventors appear similar on observables, as documented in Bell et al. (2015). Any inventor with a non-U.S. address in the USPTO patent data is excluded from the matching process and dropped from the sample. The resulting dataset is a panel of the universe of U.S.-based inventors, tracking over 750,000 inventors from 1996 to 2012. The employer ID is based on the Employer Identification Number (EIN)) reported on W-2 forms. We show in Appendix Figure E1 that the distribution of EIN size is very similar to the distribution of firm size in the Census. In the rest of the paper, we refer to business entities with distinct EINs as distinct firms.[4]

II.B Identifying Deceased Inventors, Survivor Co-inventors, Second-Degree Connections and Coworkers

We build various groups of inventors to carry out the premature death research design. We start by identifying 4,924 inventors who passed away before the age of 60 and were granted a patent by USPTO before their death.[5] Information on the year of death and age at death is known from Social Security records. The cause of death is not known. In order to reduce the likelihood that death results from a lingering health condition, we consider inventors passing away before 60 and,

[4]In some cases, it could be that business entities with different EINs are the subsidiary of the same parent company.

[5]As described below, ultimately we analyze only 4,714 premature deaths due to the lack of appropriate matches for the remaining prematurely deceased inventors. We consider prematurely deceased inventor who are weakly below 60, i.e. we keep inventors who are 60 in the year of death.

in robustness checks, we repeat the analysis by excluding deceased inventors who ever claimed tax deductions for high medical expenses.

We construct a group of "placebo deceased inventors" who appear similar to the prematurely deceased inventors but did not pass away. Specifically, we use a one-to-one exact matching procedure on year of birth, cumulative number of patent applications at the time of (real or placebo) death, and year of (real or placebo) death in order to identify placebo deceased inventors among the full population of inventors.[6] 4,714 deceased inventors find an exact match using this procedure.[7] Thus, we obtain a control group of placebo deceased inventors who have exactly the same age, the same number of cumulative patent applications and exactly the same year of (placebo) death as their associated (real) deceased inventor.

Next, we build the co-inventor networks of the real and placebo deceased inventors. Any inventor who ever appeared on a patent with a real or placebo deceased inventor before the time of (real or placebo) death is included in these networks. In the rest of the paper, we refer to these inventors as real and placebo "survivor inventors." We exclude survivor inventors who are linked to more than one real or placebo deceased inventor.[8] We thus obtain 14,150 real survivor inventors and 13,350 placebo survivor inventors. These inventors constitute the main sample used for the analysis carried out in the rest of the paper. Note that we perform the matching procedure on the real and placebo deceased inventors rather than on the survivor inventors - the benefits of this approach are discussed in Section III.

We construct two other groups of inventors, which will be used to differentiate between mechanisms. First, we build the network of inventors who are two nodes away from the real and placebo deceased inventors in the co-inventor network. These inventors are direct co-inventors of the deceased's direct co-inventors, but they never co-invented a patent with any of the (real or placebo) deceased inventors. To increase the likelihood that these inventors were never directly in contact with the deceased, we impose two additional restrictions: of the inventors who are two nodes away

[6]The match is conducted year by year. For instance, for inventors who passed away in 2000, we look for exact matches in the full sample of inventors - an exact match is found if the control inventor was born in the same year and had the same number of cumulative patent applications as the deceased in 2000. The inventors from the full sample that match are then taken out of the sample of potential matches, and the procedure is repeated for the following year, until the end of the sample. This matching procedure without replacement thus determines a counterfactual timing of death for the placebo deceased inventors. When there is more than one exact match, the ties are broken at random.

[7]The 5% unmatched deceased inventors do not significantly differ on observable characteristics from those who find a match, except that they tend to have more cumulative applications at the time of death. In robustness checks presented in Appendix E, we repeat the analysis with a propensity-score reweighting approach which uses data on all deceased inventors and obtain similar results.

[8]We lose only 36 survivor inventors by imposing this restriction.

from the deceased in the co-inventor network, we keep only those who never worked for the same employer and never lived in the same commuting zone as the deceased inventor. We refer to these inventors as real and placebo "second-degree connections" in the remainder of the paper. As before, we exclude inventors in ths group who are linked to more than one real or placebo deceased inventors. This procedure yields 11,264 real second-degree connections and 12,047 placebo second-degree connections. Second, we construct the group of "coworkers" of the deceased by identifying all inventors who worked for the same employer as the deceased in the year before death, as indicated on W-2 forms. We exclude coworkers that ever co-invented with a prematurely deceased inventor or who experienced multiple death events. Focusing on coworkers in firms with less then 2,000 employees, the final sample consists of 13,828 real coworkers and 14,364 placebo coworkers.[9]

II.C Variable Definitions and Summary Statistics

In the analysis carried out in the rest of the paper, we study various outcome variables at the individual level from 1999 until 2012. First, we consider inventors' labor earnings, which refer to annual W-2 earnings. When an inventor does not receive a W-2 form after 1999, we impute their labor earnings in that year to be zero. Second, we construct a measure of an inventors' total earnings, defined as an inventors' adjusted gross income (earnings reported on IRS tax form 1040) minus the W-2 earnings of the inventor's spouse. Adjusted gross income is a tax concept offering a comprehensive measure of a household's income, including royalties, self-employment income and any other source of income reported on 1040 tax forms.[10] We define non-labor earnings as the difference between total earnings and labor earnings. All earnings variables are winsorized at the 1% level.[11] Third, we use adjusted forward citations, which are defined for year t as the total number of forward citations received on all patents the individual applied for in year t, divided by the number of inventors who appear on each patent. Forward citations include all citations of the patent made as of December 2012 and are a measure of the "quality" of innovative output. We divide forward citations by the total number of inventors on the patent to reflect the fact

[9] We focus on smaller firms to increase the chances that we find a negative effect of an inventor's death on their coworkers, since we are interested in testing whether the effect we document for co-inventors is driven by the disruption of the firm. In Appendix E, we carry out the analysis on the full sample of coworkers, composed of 173,128 real survivor coworkers and 143,646 placebo survivor coworkers, and we find similar results. The difference in the size of the groups of real and placebo coworkers in the full sample is driven by a thin tail of deceased inventors working in firms employing thousands of other inventors, as documented in Appendix Table A5.

[10] A limitation of our measure of total earnings for inventors filing jointly is that we can only subtract the inventor's spouse's W-2 earnings from the household's adjusted gross income, not the spouse's other sources of income, which are unobserved. But the exact same procedure is applied to all inventors in the various groups we consider.

[11] We have checked that the results are robust to winsorizing at the 5% level

that a single inventor's contribution is smaller in larger teams.[12] Fourth, we use the number of patents granted by the USPTO as of December 2012, as well as the number of patents in the top 5% of the citation distribution.[13] Lastly, we create indicator variables that turn to one when labor earnings are greater than 0 or above thresholds for the 25th, 50th and 75th percentiles of the labor earnings distribution.[14] We proceed similarly for total earnings. These indicators are used as outcome variables to characterize the effect of an inventor's premature death on their co-inventors' compensation at different quantiles of the income distribution. Since labor earnings are only available from 1999 onwards, for consistency we do not use data prior to 1999 for any of the variables in the analysis, but the results are qualitatively similar when pre-1999 data is included for adjsuted gross income, patent applications and citations.

Table 1 presents summary statistics for the variables of interest in the main samples used in the analysis. Statistics on total earnings and wages are computed based on the entire panel for the full sample of inventors, and based on years before the death event for the deceased and the survivor inventors. Age, cumulative applications and cumulative citations are computed in the year of death for the deceased and the survivors, and across all years for the full sample. Appendix Table A3 presents similar statistics for the second-degree connections and coworkers.

The real deceased inventors are on average seven years older than inventors in the full sample. By construction, the distribution of age at death for the placebo deceased inventors exactly matches that of the real deceased inventors. Likewise, the distribution of the number of applications is the same for real and placebo deceased inventors. The distribution of labor earnings, total earnings and forward citations is also very similar in these two groups, although our matching algorithm did not match on these variables.

The real and placebo survivor inventors are also older than inventors in the full sample and they have much higher labor earnings and total earnings and many more patent applications and citations. The age difference is due to the fact that there is assortative matching by age in inventor teams, as documented in Section II.D, and the deceased are older than inventors in the full

[12]This is common practice. We check the robustness of our results with other measures of citations, which do not adjust for team size, take into account citations only over a fixed rolling window of a couple years around application or grant (in order to address censoring issues), and distinguish between examiner-added and applicant-added citations. Section III discusses these various robustness checks.

[13]We define the count of patents in the top 5% of citations as the number of patents the survivor inventor applied for in a given year that were in the top 5% of the citation distribution, where the distribution is computed based on all patents that were cited, applied for in the same year and in the same technology class (we aggregate USPC classes into six main technology classes, as is common in the literature). Throughout the paper, we consider only patents that were granted as of December 2012 and we use the year of filing of the patent application as the year of production of the invention.

[14]These quantiles are computed before the time of death in the population of real and placebo survivor inventors.

sample. The difference in compensation and patents is due to a selection effect: inventors who have co-invented many patents are more likely to experience the (real or placebo) death of one of their co-inventors. Therefore, it would not be appropriate to use the full population of inventors as a control group for the real survivor inventors, as their lifecycle earnings are likely to be on different trajectories. In contrast, the distributions of labor earnings, total earnings, age and patent applications and citations are very similar in the group of placebo survivors and real survivors. Importantly, our matching algorithm did not impose that any of the characteristics of the placebo survivor inventors should be aligned with those of the real survivor inventors, since we matched on characteristics of the real and placebo deceased only. Labor earnings are slightly lower for the real survivors compared to the placebo survivors, but we will check in Section III that this difference is constant during years prior to co-inventor death, consistent with the assumptions of the difference-in-differences research design. Appendix Tables A1 and A2 show that the real and placebo survivors are also similar in terms of the year of co-inventor death, their technology class specialization, the size of their co-inventor networks and the size of their firms.

II.D Descriptive Statistics on Patent Inventor Teams

Most inventors work in teams: 55% of the 1,375,587 patents in our data are produced by teams, i.e. more than one inventor is listed on the patent. Moreover, team composition shows a significant degree of persistence. In our sample, considering teams that applied for a patent in 2002, the probability that another patent applied for by a member of the team between 1997 and 2007 also includes at least one other member of the 2002 team is 30.4%. When conditioning on patents that were assigned to different assignees[15], the percentage falls but remains high, at 21.6%. This suggests that teams are persistent across firm boundaries.[16]

There is wide variation in the composition of inventor teams. Taking teams of two inventors in 2002 as an example, Figure 1 shows the distribution of absolute differences between team members in total earnings, labor earnings and age. The mean age difference between inventors in these teams is 10, with a standard deviation of 15. In one-fourth of these teams, the age difference is three years or less and the difference in labor earnings is below $25,000. But in another fourth of these teams, the age difference is larger than 14 years and the difference in labor earnings is above $120,000. Therefore, it is true that inventors who are similar in characteristics like age and compensation tend

[15] Assignees are the legal patent holders and are typically the employers of the inventors on the patents.

[16] Similar results are obtained when considering other application years as the year of reference. Appendix Table E6 documents that many teams span more than one EIN, which means they most likely cross firm boundaries.

to work together, but only up to a point. Appendix E reports additional results and the findings are qualitatively similar when considering other years and larger teams.

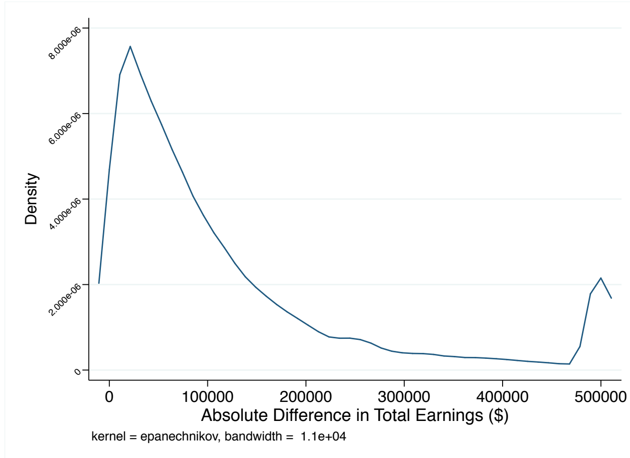
Table 1: Summary Statistics

Variable	Sample	Mean	SD	10pc	25pc	50pc	75pc	90pc
Total Earnings	Full Sample	144,096	316,636	38,000	58,000	110,000	163,000	241,000
	Real Deceased	139,857	308,000	35,000	59,000	105,000	160,000	237,000
	Placebo Deceased	139,102	320,970	36,000	58,000	104,000	162,000	236,000
	Real Survivors	177,020	355,347	48,000	89,000	125,000	173,000	270,000
	Placebo Survivors	177,247	360,780	47,000	89,000	125,000	173,000	271,000
Labor Earnings	Full Sample	117,559	257,466	25,000	46,000	90,000	142,000	202,000
	Real Deceased	121,691	258,289	29,000	50,000	99,000	147,000	210,000
	Placebo Deceased	124,149	248,546	33,000	52,000	101,000	148,000	210,000
	Real Survivors	152,602	295,832	42,000	78,000	113,000	160,000	239,000
	Placebo Survivors	155,098	290,201	44,000	80,000	116,000	162,000	242,000
Cumulative Applications	Full Sample	2.31	2.51	0	1	1	3	7
	Real Deceased	2.50	2.43	0	1	1	3	7
	Placebo Deceased	2.50	2.43	0	1	1	3	7
	Real Survivors	12.42	28.31	1	2	5	13	28
	Placebo Survivors	11.92	29.52	1	2	5	13	27
Cumulative Citations	Full Sample	6.64	12.2	0	0	1	6.58	23.5
	Real Deceased	8.74	13.09	0	0	3	10	29.13
	Placebo Deceased	8.51	13.20	0	0	2.5	9.95	30
	Real Survivors	42.00	171.03	0.25	1.3	7	28.5	89.53
	Placebo Survivors	40.20	164.20	0.32	1.5	7	29.5	85.32
Age	Full Sample	43.29	9.65	30	36	44	51	56
	Real Deceased	50.85	7.44	40	46	52	57	59
	Placebo Deceased	50.85	7.44	40	46	52	57	59
	Real Survivors	47.53	10.89	35	41	48	55	61
	Placebo Survivors	47.289	11.16	34	41	47	55	60
# Inventors	Full Sample	756,118						
	Real Deceased	4,714						
	Placebo Deceased	4,714						
	Real Survivors	14,150						
	Placebo Survivors	13,350						

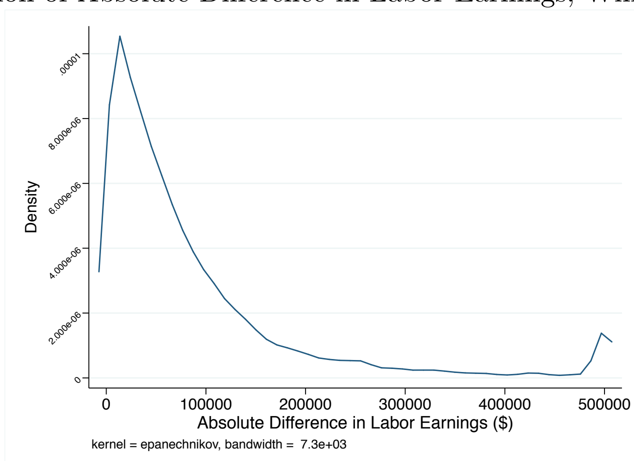
Notes: This table reports summary statistics for the various groups of inventors defined in Section II.B. The statistics for the full sample are computed using data from 1999 to 2012. For the deceased and survivor inventors, the statistics are computed using data before the year of death. Dollar amounts are reported in 2012 dollars and are rounded to the nearest $1,000 to preserve taxpayer confidentiality. The balance between real and placebo survivors is qualitatively similar when considering the exact percentile values. Appendix Tables A1 and A2 document balance between real and placebo deceased and survivor inventors for additional covariates. Appendix Table A3 reports summary statistics for the other groups of inventors described in Section II.B. For a detailed description of the data sources and sample construction, see Sections II.A and II.B.

Figure 1: Team Composition for Two-Inventor Teams in 2002

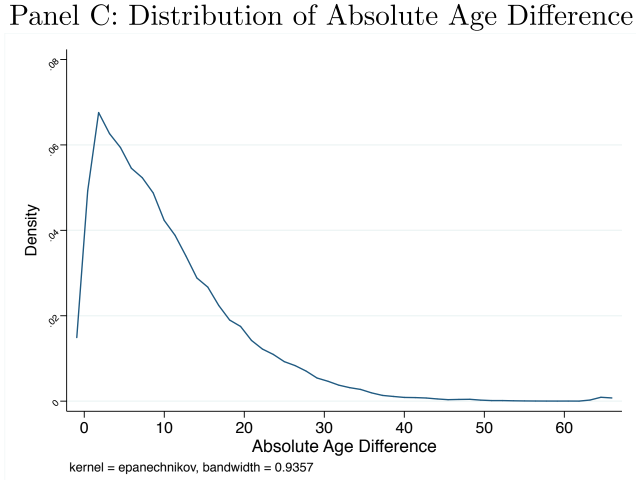
Panel A: Distribution of Absolute Difference in Total Earnings, Winsorized at $500,000



Panel B: Distribution of Absolute Difference in Labor Earnings, Winsorized at $500,000



Panel C: Distribution of Absolute Age Difference



Notes: This figure shows the Epanechnikov kernel density of the absolute differences in total earnings, labor earnings and age between the inventors listed on a two-inventor patent. The sample is the population of inventors residing in the US who invented a patent with exactly one co-inventor in 2002. There are 23,210 such patents. The earnings differences are winsorized at $500,000, hence the point mass at the right of the distributions. Appendix E reports additional summary statistics on team composition.

III Estimating the Causal Effect of the Premature Death of a Co-Inventor on an Inventor's Compensation and Patents

This section presents our methodology to estimate the average treatment effect of experiencing death of a coauthor on labor earnings, total earnings, patents and citation-weighted patents. It then describes our main results and a series of robustness checks.

III.A Research Design

We want to build the counterfactual of compensation and patent production for (real) survivor inventors, had they not experienced the premature death of a co-inventor. Two main challenges arise to identify this causal effect. First, the real survivor inventors are on a different earnings and patent trajectory than the full population of inventors. To address this challenge, we use the control group of placebo survivor inventors described in Section II in a difference-in-differences research design. Second, death may not be exogenous to collaboration patterns.[17] We show that the estimated causal effects of co-inventor death are significant only after the year of death, which alleviates this concern.

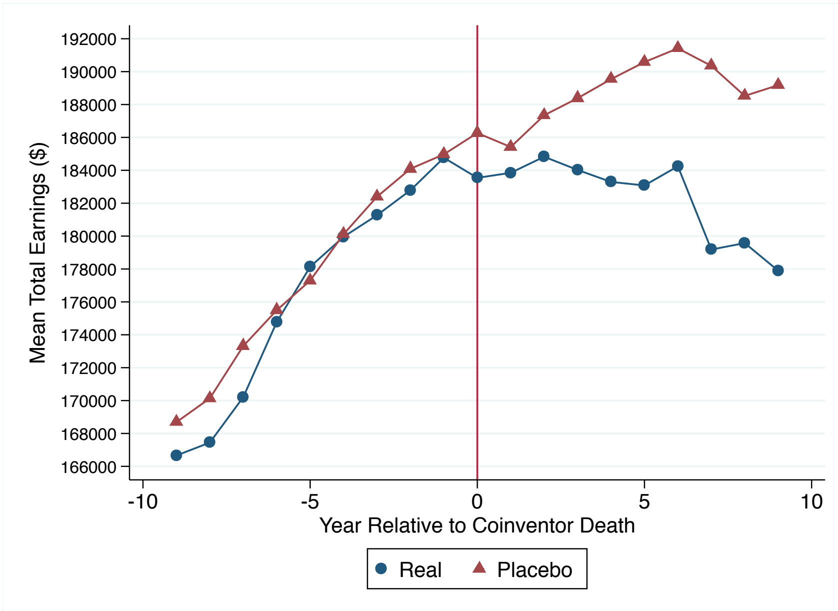
Figure 2 confirms non-parametrically that the real and placebo survivor inventors are on similar earnings and patent trajectories before the time of co-inventor death and sharply differ afterwards.[18] This bolsters the validity of the research design, especially given that our match algorithm did not use any information on survivor inventors. Real and placebo survivors have similar levels of total earnings before death, but placebo survivors have higher labor earnings than the real survivors before death, indicating that real survivors have a higher share of their total earnings in the form of non-labor earnings . The difference in labor earnings appears roughly constant, at around $2,500 (about 2% of labor earnings). In our regression framework, we use individual fixed effects to absorb this difference.

[17] We cannot think of very convincing examples of why this could be the case, but perhaps a particularly bad collaboration may result in an inventor's death. For a discussion of how pre-trends can be interpreted as anticipation rather than endogeneity of treatment, see Malani and Reif (2015).

[18] The figure plots the raw data, without imposing that mean outcomes in the treatment and control groups should be equal prior to death.

Figure 2: Path of Outcomes Around Co-inventor Death

Panel A: Survivor Inventor's Total Earnings



Panel B: Survivor Inventor's Labor Earnings

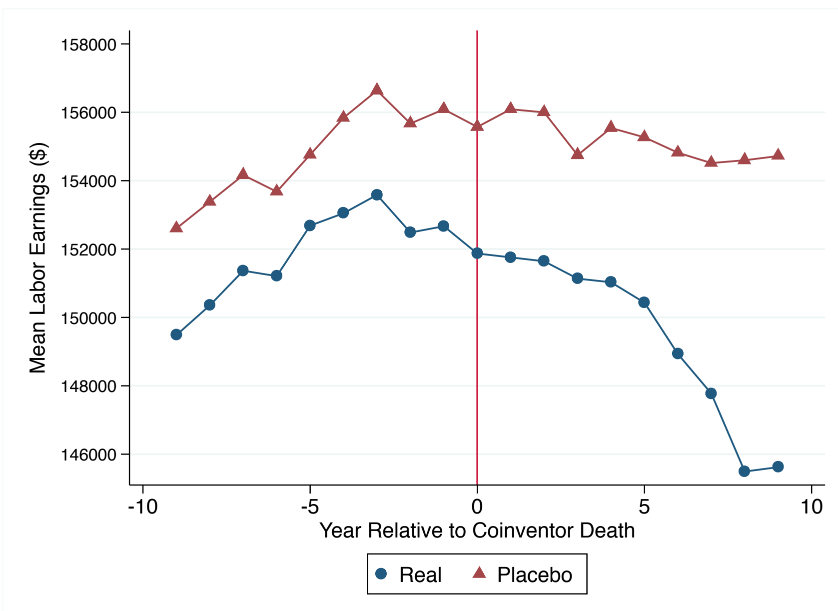
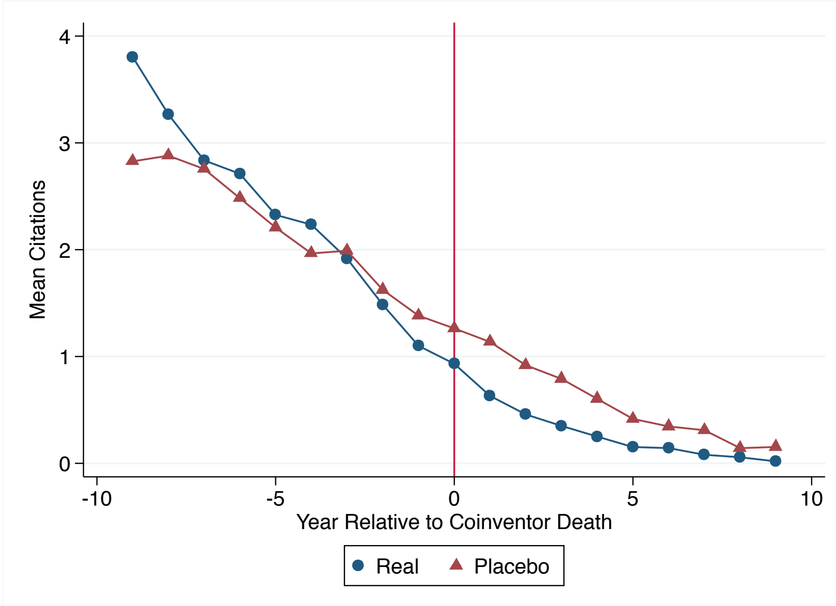


Figure 2: Path of Outcomes Around Co-inventor Death *(continued)*

Panel C: Survivor Inventor's Adjusted Forward Citations Received for Patents Applied in Year



Notes: Panels A to C of this figure show the path of mean total earnings, labor earnings and citations for real and placebo survivor inventors around the year of co-inventor death. The sample includes all real and placebo survivor inventors in a 9-year window around the year of co-inventor death, i.e. inventor-year observations are dropped when the lead or lag relative to co-inventor death is above 9 years. The unbalanced nature of this panel is the same for real and placebo inventors. Appendix Table B2 shows that the results are similar on a balanced sample. Dollar amounts are reported in 2012 dollars. Refer to Section II.B for more details on the sample and to Section II.C for more details on the outcome variables.

Figure 2 shows that the earnings profile of survivor inventors flattens out after the time of death, even for the placebo survivor inventors. This may be due to curvature in the age profile of earnings, year fixed effects, or mechanical effects induced by the construction of the sample of survivors. Citations are declining over time, probably primarily due to censoring (patents applied for and granted near the end of our sample do not have the opportunity of being cited). Our regression framework takes all of these effects into account.

Figure 2 offers a transparent depiction of the data and is useful in gauging the magnitude of the causal effect of co-inventor death on total earnings, labor earnings and forward adjusted citations. However, it is not well suited to a precise estimation of the causal effect - since covariates like age are not perfectly balanced across treated and control groups - nor to robust inference. Two types of clusters are important to take into account for inference: even after controlling for a battery of fixed effects, there may be serial correlation in an inventor's outcomes over time and the outcomes of inventors linked to the same deceased may be correlated. We cluster standard errors at the level of the deceased inventors, which takes into account both forms of clustering.[19]

III.B Regression Framework

In order to study the dynamics of the effect, while at the same time probing the validity of the research design by testing whether there appears to be any effect of losing a co-inventor before the event actually occurs, we use a panel data model based on five elements, whose relevance has been discussed in the previous subsection. First, we include a full set of leads and lags around co-inventor death for real survivor inventors (L_{it}^{Real}). The predictive effects associated with these leads and lags are denoted $\{\beta^{Real}(k)\}_{k=-9}^{9}$, where k denotes time relative to death.[20] If the identification assumption described below holds, $\beta^{Real}(k)$ denotes the causal effect of co-inventor death on the outcome of interest k years after death. Second, we use a full set of leads and lags around co-inventor death that is common to both real and placebo survivors (L_{it}^{All}) - the corresponding predictive effects are denoted $\{\beta^{All}(k)\}_{k=-9}^{9}$. Lastly, we introduce three distinct sets of fixed effects: age fixed effects (a_{it}), year fixed effects (γ_t) and individual fixed effects (α_{it}).

We assume separability[21] and specify the conditional expectation functions as follows:

$$E[Y_{it}|L_{it}^{Real}, L_{it}^{All}, a_{it}, t, i] = f(L_{it}^{Real}) + f(L_{it}^{All}) + g(a_{it}) + \gamma(t) + \alpha_i$$

We then estimate the model with a full set of fixed effects by OLS:[22]

$$Y_{it} = \sum_{k=-9}^{9} \beta_k^{Real} 1_{\{L_{it}^{Real}=k\}} + \sum_{k=-9}^{9} \beta_k^{All} 1_{\{L_{it}^{All}=k\}} + \sum_{j=25}^{70} \lambda_j 1_{\{age_{it}=j\}} + \sum_{m=1999}^{2012} \gamma_m 1_{\{t=m\}} + \alpha_i + \epsilon_{it} \quad (1)$$

The main difference between our specification and the specifications used in the existing literature relying on premature deaths for identification is that we include a set of leads and lags around death that is common to both real and placebo survivors (L_{it}^{All}), in addition to the set of

[19]We are close to observing the population of patent inventors who passed away prematurely between 1996 and 2012. Therefore, we interpret our standard errors with respect to their superpopulation. In Appendix Table B10, we use the coupled bootstrap procedure of Abadie and Spiess (2015) to estimate standard errors taking into account the matching step.

[20]We drop observations where k is below -9 or above +9 because there are too few observations far away from death and the coefficients on these leads and lags are therefore imprecisely estimated. Results are qualitatively similar when all observations are kept.

[21]The results are qualitatively similar when interacting age and year fixed effects.

[22]We exclude observations with inventors below the age of 25 or above the age of 70 from the sample to reduce variance, but the results are similar when these observations are included. When the dependent variable is citation or patent counts, we use a Poisson estimator, with QMLE standard errors clustered at the deceased-inventor level. The Poisson estimator with individual fixed effects fails to converge in our sample, therefore we report results without individual fixed effects and, as a robustness check, we run the same specifications with a negative binomial estimator with fixed effects.

leads and lags around co-inventor death for the real survivors (L_{it}^{Real}). This application of the standard difference-in-differences estimator[23] to our setting addresses the concern that age, year and individual fixed effects may not fully account for trends in life-time earnings and patents around co-inventor death. An inventor must necessarily have invented a patent before the year of (real or placebo) co-inventor death and is more likely to have been employed at that time, even conditional on a large set of fixed effects. Therefore, the construction of the sample of survivor inventors might mechanically induce a bias that the fixed effects do not fully address, and indeed we find that the set of leads and lags L_{it}^{All} has substantial predictive power for certain outcomes like employment. Intuitively, the leads and lags that are common to both real and placebo survivors (L_{it}^{All}) capture the mechanical effects, while the leads and lags that are specific to the real survivors (L_{it}^{Real}) capture the causal effect of co-inventor death.

Formally, if $E[1_{\{L_{it}^{All}=k\}}\epsilon_{it}|L_{it}^{Real}, L_{it}^{All}, a_{it}, t, i] = 0 \ \forall(t,k)$, then $\beta^{Real}(k)$ gives the causal effect of co-inventor death on the outcome of interest k years after death. Appendix D formally derives what is identified in this model and how the predictive effects $\{\beta^{Real}(k)\}_{k=-9}^{9}$ can be used to probe the validity of the research design and identify causal effects. It also compares our specification to those commonly used in the literature using premature deaths for identification.

In the next subsection, we use specification (1) to confirm the validity of the research design and study the dynamics of the effect. To summarize the results and discuss magnitudes, we employ a second specification, with a dummy turning to one after the time of co-inventor death for real survivor inventors ($AfterDeath_{it}^{Real}$) and another dummy turning to one after the time of co-inventor death for both real and placebo survivor inventors ($AfterDeath_{it}^{All}$). Under our identification assumption, β^{Real} gives the average causal effect of death.[24] This specification is as follows:

$$Y_{it} = \beta^{Real} AfterDeath_{it}^{Real} + \beta^{All} AfterDeath_{it}^{All} + \sum_{j=25}^{70} \lambda_j 1_{\{age_{it}=j\}} + \sum_{m=1999}^{2012} \gamma_m 1_{\{t=m\}} + \alpha_i + \epsilon_{it} \quad (2)$$

III.C Results

Figure 3 reports the point estimates and 95% confidence interval for the coefficients β_k^{Real}, obtained from specification (1). Four outcome variables are considered: total earnings, labor earnings, non-

[23]In the standard difference-in-difference estimator, treatment occurs at only one point in time and the regression includes an $After$ dummy and a $After \times Post$ dummy. In our setting, where co-inventors death are scattered over time, L_{it}^{All} plays a role analogous to the $After$ dummy and L_{it}^{Real} plays a role analogous to the $After \times Post$ dummy.

[24]We have relatively more deaths occurring later in our sample and, as a result, β^{Real} gives more weight to the causal effects of death in the short-run after death and less weight to long-run effects. All results in the paper are about the average treatment effect on the treated.

labor earnings and citations. The point estimate on the lag turning to one in the year preceding death is normalized to 0 and inference is carried out relative to this lag.[25] We observe no pre-trending for any of the outcome variables, which lends credibility to the research design. The effect of co-inventor death on compensation and patents appears to manifest itself gradually: total earnings, labor earnings, non-labor earnings and citations all start to decline gradually after the death of a co-inventor. Consistent with the event studies in Figure 2, the nonparametric fixed effects for each lead and lag around death thus indicate that the nature of the effect is a change in the slope of the outcomes, rather than a level shift, and that co-inventor death has effects beyond short-term disruption of teamwork.

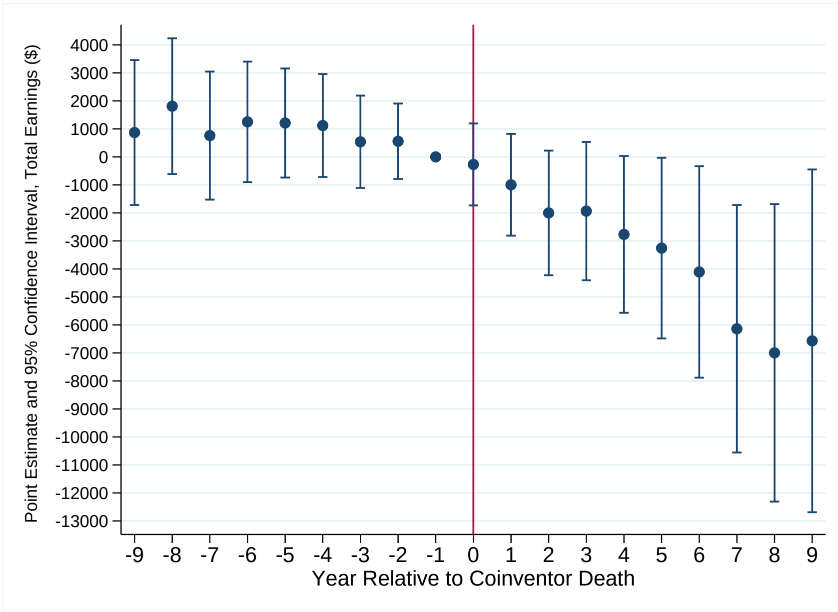
The magnitude of the effects is large. Eight years after the time of co-inventor death, the real survivor inventors' total earnings is \$7,000 lower (4% of mean total earnings in the sample of survivors), their labor earnings are about \$5,800 lower (3.8% of mean labor earnings in the sample of survivors) and their citation-weighted patent production is 15% lower than it would have been had they not experienced the premature death of a co-inventor. About 80% of the total decline in earnings is due to decline in labor earnings. We formally test the hypotheses that the point estimates are all the same before and after co-inventor death with a F-test, reported in Appendix Table B1 - we can never reject that the point estimates are all similar before death, but we can after death.

In order to reduce noise, we use specification (2), with a single indicator turning to one after the year of co-inventor death for real survivor inventors. The results are reported in Tables 2. We use thresholds corresponding to the extensive margin, the 25th, 50th and 75th percentiles of the total earnings and labor earnings distributions to characterize heterogeneity in the effect across the income distribution.

[25] The full set of leads and lags L_{it}^{Real} always sum up to one for the survivor inventors and our specification includes individual fixed effects, therefore one of the leads and lags must be "normalized" to one. Appendix D discusses this standard normalization more formally.

Figure 3: Dynamic Causal Effects of Co-inventor Death

Panel A: Survivor Inventor's Total Earnings



Panel B: Survivor Inventor's Labor Earnings

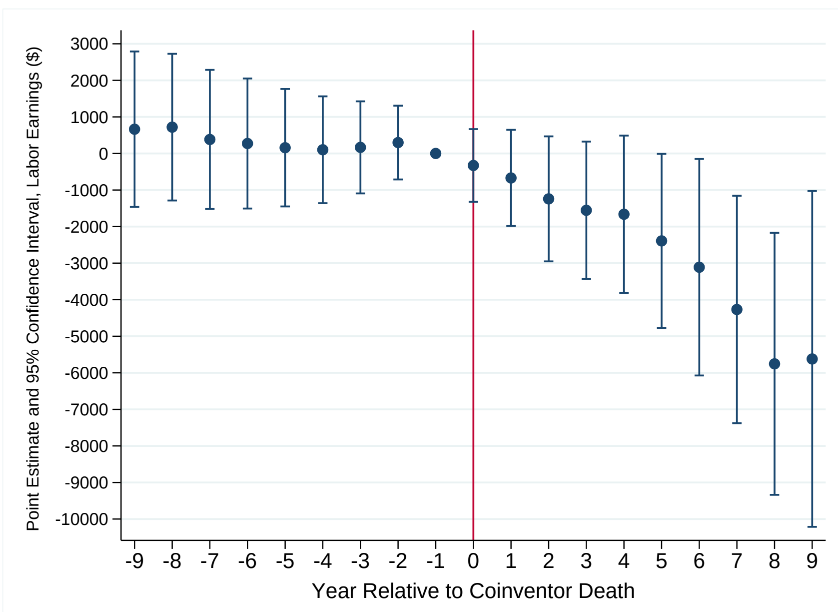
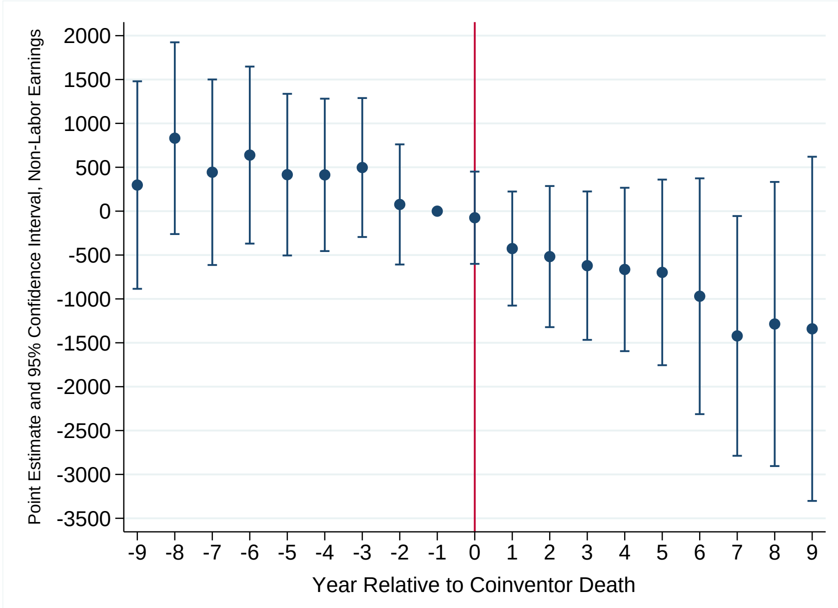
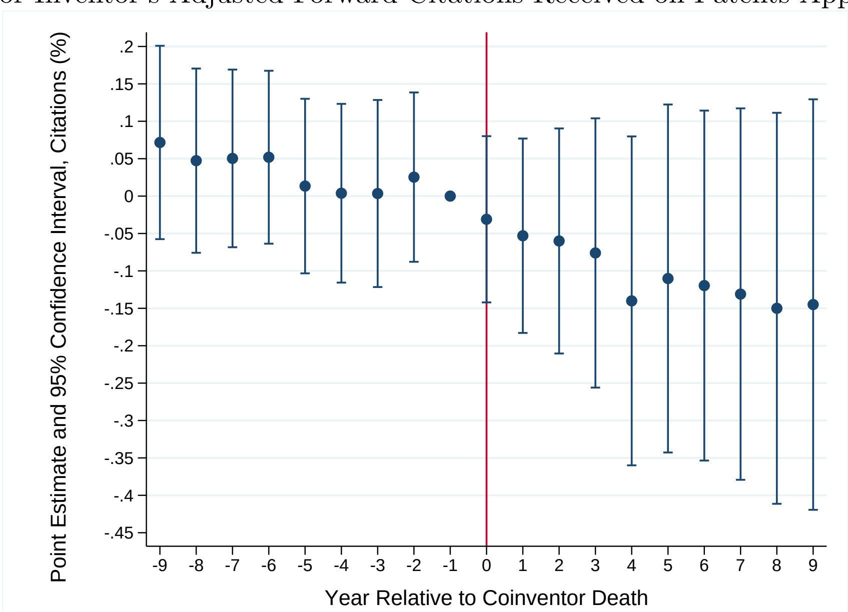


Figure 3: Dynamic Causal Effects of Co-inventor Death *(continued)*

Panel C: Survivor Inventor's Non-Labor Earnings



Panel D: Survivor Inventor's Adjusted Forward Citations Received on Patents Applied For in Year



Notes: Panels A to D of this figure shows the estimated β_k^{Real} coefficients from specification (1) for four outcome variables. Standard errors are clustered around the deceased inventors. Under the identification assumption described in Section III.B, β_k^{Real} gives the causal effect of co-inventor death in year k relative to co-inventor death. In panel D, the outcome variable is the count of forward citations received on patents the survivor applied for in a given year. Therefore, this variable reflects the timing and quality of patent applications by the survivor, not the timing of citations. Dollar amounts are reported in 2012 dollars. The sample includes all real and placebo survivor inventors in a 9-year window around the year of co-inventor death, i.e. inventor-year observations are dropped when the lead or lag relative to co-inventor death is above 9 years. The unbalanced nature of this panel is the same for real and placebo inventors. Appendix Table B2 shows that the results are similar on a balanced panel. For more details on the outcome variables, refer to Section II.C.

Table 2: Causal Effects of Co-inventor Death

Panel A: Survivor Inventor's Total Earnings and Non-Labor Earnings

	Total Earnings	>p25	>p50	>p75	Non-Labor Earnings
$AfterDeath^{Real}$	-3,873***	-0.01531***	-0.0107**	-0.00772**	-1,199**
s.e.	(910)	(0.00434)	(0.00457)	(0.0039)	(498)
$AfterDeath^{All}$	- 223	0.00036	0.00066	-0.00068	651*
s.e.	(537)	(0.00285)	(0.00314)	(0.00297)	(378)
Age and Year Fixed Effects	Yes	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	Yes	Yes
# Observations	325,726	325,726	325,726	325,726	325,726
# Survivors	27,500	27,500	27,500	27,500	27,500
# Deceased	9,428	9,428	9,428	9,428	9,428
Estimator	OLS	OLS	OLS	OLS	OLS

Notes: This table reports the estimated coefficients β^{Real} and β^{All} from specification (2). Column 1 reports the results for total earnings and column 5 for non-labor earnings. The outcome variables for columns 2 to 4 are indicator variables equal to one when the inventor's total earnings are above the specified quantile of the total earnings distribution. The dollar value of these quantiles is reported in Table 1. Under the identification assumption described in Section III.B, β^{Real} gives the causal effect of co-inventor death on these various outcomes. The sample includes all real and placebo survivor inventors in a 9-year window around the year of co-inventor death, i.e. inventor-year observations are dropped when the lead or lag relative to co-inventor death is above 9 years. The unbalanced nature of this panel is the same for real and placebo inventors. Appendix Table B2 shows that the results are similar on a balanced panel. Dollar amounts are reported in 2012 dollars. Standard errors are clustered around the deceased inventors. $*p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Panel B: Survivor Inventor's Labor Earnings

	Labor Earnings	>0	>p25	>p50	>p75
$AfterDeath^{Real}$	-2,715***	-0.00913***	-0.01039**	-0.007203*	-0.00638*
s.e.	(706)	(0.00315)	(0.00411)	(0.0037)	(0.00342)
$AfterDeath^{All}$	-38	-0.0051**	-0.00259	-0.00066	0.00127
s.e.	(480)	(0.00221)	(0.00295)	(0.00322)	(0.003)
Age and Year Fixed Effects	Yes	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	Yes	Yes
# Observations	325,726	325,726	325,726	325,726	325,726
# Survivors	27,500	27,500	27,500	27,500	27,500
# Deceased	9,428	9,428	9,428	9,428	9,428
Estimator	OLS	OLS	OLS	OLS	OLS

Notes: This table reports the estimated coefficients β^{Real} and β^{All} from specification (2). Column 1 reports the results for labor earnings. In column 2, the outcome variable is an indicator equal to one when the inventor receives a W-2, i.e. has positive labor earnings. The outcome variables for columns 3 to 5 are indicator variables equal to one when the inventor's labor earnings are above the specified quantile of the labor earnings distribution. The dollar value of these quantiles is reported in Table 1. Under the identification assumption described in Section III.B, β^{Real} gives the causal effect of co-inventor death on these various outcomes. Appendix Table B2 shows that the results are similar on a balanced panel. Dollar amounts are reported in 2012 dollars. Standard errors are clustered around the deceased inventors. $*p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 2: Causal Effects of Co-inventor Death *(continued)*

Panel C: Survivor Inventor's Patent Applications and Forward Citations

	Patent Count	Citation Count	Count of Patents with No Citations	Count of Patents in Top 5% of Citations
$AfterDeath^{Real}$	-0.09121***	-0.09024***	-0.07656***	-0.02182***
s.e.	(0.02063)	(0.02326)	(0.0217)	(0.00789)
$AfterDeath^{All}$	0.00055	0.04084	0.00325	0.00455
s.e.	(0.01776)	(0.03016)	(0.02662)	(0.00554)
Age and Year Fixed Effects	Yes	Yes	Yes	Yes
Individual Fixed Effects	No	No	No	No
# Observations	325,726	325,726	325,726	325,726
# Survivors	27,500	27,500	27,500	27,500
# Deceased	9,428	9,428	9,428	9,428
Estimator	Poisson	Poisson	Poisson	Poisson

Notes: This table reports the estimated coefficients β^{Real} and β^{All} from specification (2), except that it does not include individual fixed effects because the Poisson estimator with individual fixed effects did not converge for several outcome variables. Appendix Table B8 shows that the results are similar with individual fixed effects, using a negative binomial estimator. The four outcome variables are as follows: (1) patent count is the number of patents the survivor inventor applied for in a given year; (2) citation count is the number of forward citations received on patents that the survivor applied for in a given year (therefore, this variable reflects the timing and quality of patent applications by the survivor, not the timing of citations); (3) the count of patents with no citations is the number of patents that the survivor inventor applied for in a given year and that have never been cited as of December 2012; (4) the count of patents in the top 5% of citations is the number of patents the survivor inventor applied for in a given year that were in the top 5% of the citation distribution, where the distribution is computed based on all patents that were cited, applied for in the same year and in the same technology class (we aggregate USPC classes into six main technology classes, as is common in the literature). Under the identification assumption described in Section III.B, β^{Real} gives the causal effect of co-inventor death on these various outcomes. The sample includes all real and placebo survivor inventors in a 9-year window around the year of co-inventor death, i.e. inventor-year observations are dropped when the lead or lag relative to co-inventor death is more than 9 years. The unbalanced nature of this panel is the same for real and placebo inventors. Appendix Table B2 shows that the results are similar on a balanced panel. Standard errors are clustered around the deceased inventors. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 2 shows large and statistically significant coefficients β^{Real} for all outcome variables, consistent with the dynamic specifications reported in Figure 3. The effect exists across the distribution of adjusted gross income, and it seems larger in lower quantiles - a finding we will probe further in Section IV. Interestingly, β^{All} is significant for two outcomes: non-labor earnings and the extensive margin of labor earnings. The point estimates are large in magnitude relative to the point estimates for β^{Real}, which shows that controlling for mechanical patterns is important to avoid bias, even when age, year and individual fixed effects are included. Panel C of Table 2 shows that co-inventor death has large and significant effects for both the quantity of quality of patents produced by survivor inventors.[26]

[26]The results for β^{Real} reported in Table 2 are the same when running the following specification, which replaces

III.D Robustness Checks

Balanced Panel. We have confirmed that our results are robust to restricting attention to a balanced panel, focusing on survivors whose associated deceased passed away between 2003 and 2008 and considering a four-year window around death for each of these survivors. The results are presented in Appendix Table B2 and are similar to the results using the unbalanced panel.

Dynamics. The finding that co-inventor death has a long-lasting effect is one of the most striking results of this paper. Appendix Table B3 confirms that the effect becomes larger over time in a statistically significant way, using a specification with an indicator turning to one for observations more than four years after death (which reduces the noise reflected by the standard errors shown on Figure 2). A potential concern when studying the dynamics of the effect is related to how unbalanced the panel is with respect to years before and after the death of the co-inventor. For example, recent deaths have many pre-death observations but few post-death observations while the opposite holds for early deaths in the sample. The dynamic specification can confound true dynamics due to the changing composition of the sample.[27] To address this issue, Figure 4 shows the path of total earnings for real and placebo survivor inventors experiencing death of their co-inventor between 2003 and 2005. This allows us to track the same individuals over time and confirms that the effect of coauthor death is indeed gradual and long-lasting. The regression results are presented in Appendix Table B4 and are qualitatively similar to the findings reported in Figure 3.

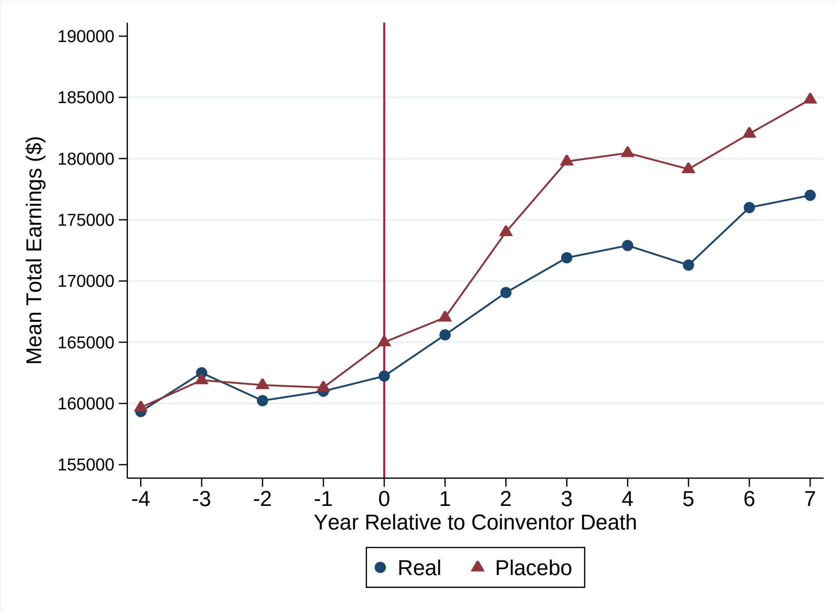
$AfterDeath_{it}^{All}$ in specification (2) with a full set of leads and lags around death (L_{it}^{All}):

$$Y_{it} = \beta^{Real} AfterDeath_{it}^{Real} + \sum_{k=-9}^{9} \beta_k^{All} 1_{\{L_{it}^{All}=k\}} + \sum_{j=25}^{70} \lambda_j 1_{\{age_{it}=j\}} + \sum_{m=1999}^{2012} \gamma_m 1_{\{t=m\}} + \alpha_i + \epsilon_{it}$$

We have also checked that the results obtained with the Poisson estimator for count data are qualitatively similar when using OLS instead.

[27] For example, it could be that inventors who experience death of a coauthor earlier in the sample are of higher ability than inventors who experience death of a coauthor later in the sample, which would manifest itself as larger long-run than short-run effects of death that are entirely due to changing sample composition rather than dynamic cumulative impacts. Similarly, one could imagine that earlier deaths in the sample had a bigger impact than later deaths but the impacts are constant following death: again, this would induce larger long-run than short-run effects, resulting from changing composition rather than dynamic cumulative impacts.

Figure 4: Path of Total Earnings for Survivors with Co-inventor Death in 2003-2005



Notes: This figure shows the path of mean total earnings for real and placebo survivor inventors around the year of co-inventor death. The sample is restricted to the 4,812 co-inventors of the 1,764 real and placebo deceased with a year of death between 2003 and 2005. Inventor-year observations are dropped if the lag relative to co-inventor death is greater than seven years or if the lead relative to death is greater than four years. The panel is balanced: we observe the same inventors over a period of twelve years. Appendix Table B4 reports the results of the regression analysis in this sample.

Anticipation. Another potential concern with our design is that co-inventor death may result from lingering health condition. To investigate this hypothesis, we study tax deductions for high medical expenditures claimed by the deceased on their personal income tax return.[28] As shown in Appendix Figure B1, we find that seventy-five percent of deceased inventors do not claim any such deduction, but twenty-five percent claim a deduction in the year preceding death as well as in the year of death, and a small number claim deductions starting several years before death. As a robustness check, we repeat our analysis by excluding survivors whose associated deceased had a positive amount of tax deductions for high medical expenses in any year before death. We find that our results strengthen, as shown in Appendix Table B5. Intuitively, when the co-inventor is impaired before the time of death, our estimate of the causal effect on the survivors is biased downward because part of the effect starts before the time of death.

Matching Strategy. We have investigated an alternative matching strategy, identifying a control group of placebo survivor inventors using propensity score reweighting, after estimating

[28] This information is available on IRS form 1040.

the propensity score on total earnings, labor earnings, year of birth and patent applications of the deceased inventors in the years preceding death. The results with this empirical strategy are reported in Appendix Figure B2 and Appendix Table B6 and are similar to the results using the real and placebo deceased exact match strategy.

Citations. Appendix Table B7 reports the causal effect of co-inventor death on a series of alternative measures of citations. Specifically, we consider in turns measures of citations that count only citations received in 3-year or 5-year citation windows after the time of grant or application (in order to address censoring), and that take into account only applicant-added or examiner-added citations. We find a large and statistically-significant effects, with magnitudes similar to Table 2. Appendix Table B8 shows the robustness of the citation results using a negative binomial estimator with individual fixed effects instead of a Poisson estimator.

Technology Classes. We check that our results are consistent across technology classes. Appendix Table B9 shows that, for the various outcome variables of interest, the effect of co-inventor death is not significantly different across technology classes. Our results are therefore not driven by a particular technology class.

Inference Taking into Account the Match Step. Lastly, we implement the coupled bootstrap procedure presented in Abadie and Spiess (2015) so that our standard errors reflect the matching step. The results are robust, with slightly smaller standard errors as shown in Appendix Table B10.

IV Distinguishing Between Mechanisms

In this section, we show that the gradual decline in earnings and citations caused by the premature death of a co-inventor stems from the fact that the survivor lost a co-inventor with whom they were collaborating extensively. We first rule out alternative mechanisms that are not specific to the team, establishing that the effect does not result from the disruption of the firm or from diffuse network effects. Second, we show that the effect is not driven by asymmetric top-down spillovers from unusually high-achieving deceased inventors. Third, we demonstrate that the intensity of the collaboration between the deceased and the survivor inventors prior to death is an important predictor of the magnitude of the effect. Fourth, we document that the majority of the effect results from the fact that the survivor can no longer co-invent with the deceased. Indeed, when considering only patents that were invented by the survivor without the deceased, the effect becomes much smaller. We also show that team-specific capital spans firm and geographic boundaries. Finally, we discuss other possible mechanisms consistent with the evidence.

IV.A Firm Disruption and Network Effects Are Not the Primary Mechanism

To test whether the effect documented in Section III results from the disruption of the firm or from diffuse network effects, we consider the groups of real and placebo coworkers and second-degree connections.[29] Figure 5 shows that the real and placebo coworkers (Panels A to C) and the real and placebo second-degree connections (Panels D to F) follow similar earnings and citation paths both before and after the year of death of their associated deceased.[30] This stands in sharp contrast with the diverging paths of real and placebo survivors after co-inventor death, as presented in Figure 3.

Table 3 reports the results obtained from specification (2) and shows that the premature death of an inventor has no significant negative effect on their coworkers and second-degree connections. The point estimates for the various outcome variables are generally one or two orders of magnitude smaller than the point estimates obtained for the direct co-inventors and are relatively precisely estimated.

For the coworkers, we find small and significant *positive* effects of an inventor's death on their coworkers' likelihood of being employed as well as on their patent and citation counts. Therefore, the large negative effect on the direct co-inventors of the deceased documented in Section III do not result from the disruption of the firm or the R&D lab following an inventor's death.[31] The positive effect on coworkers may result from substitutability between inventors at the same firm: an inventor's earnings and patent production might rise after the death of a coworker because it increases this inventor's chance of being promoted and their access to resources within the firm.[32]

[29]The coworkers are the inventors who were in the same firm as the deceased in the year prior to death. The second-degree connection are the co-inventors of the co-inventors of the deceased. Refer to Section II for more details about the definition of these groups and the construction of the sample.

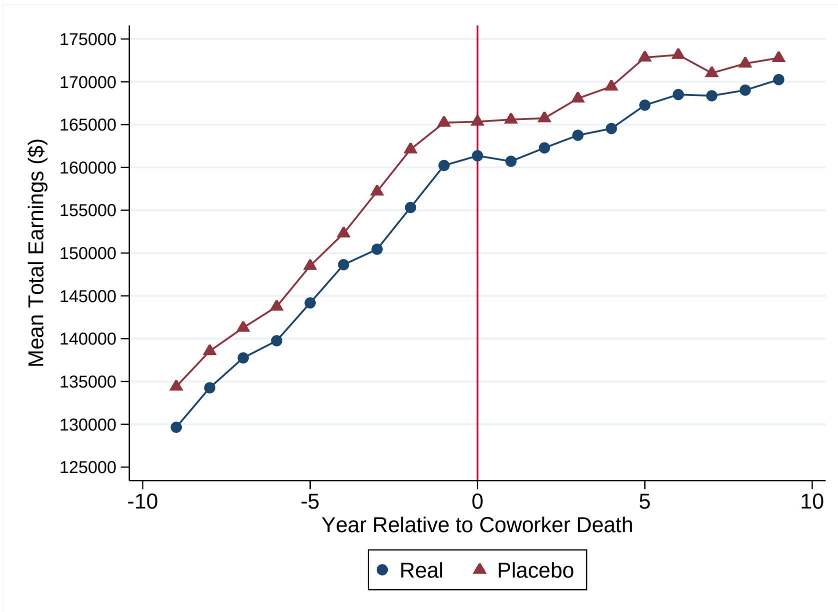
[30]The path of earnings for coworkers and second-degree connections - whether real or placebo - exhibits strong curvature around the time of (real or placebo) death. This curvature is partly captured by year and age effects. It also results from the fact that we impose that the coworkers should be employed in the year preceding death and that the second-degree connection should have co-invented with the survivors prior to death.

[31]We provide additional evidence confirming this fact by showing that the effect persists for co-inventors located in different firms at the time of death (Table 9) and that the magnitude of the effect is not correlated with firm size (Appendix Table C6).

[32]Further exploration of the mechanism at play for coworkers is beyond the scope of this paper, but our results are consistent with those obtained in parallel work by Jaeger (2015), who studies small firms in Germany rather than the population of inventors, as we do.

Figure 5: Path of Outcomes for Coworkers and Second-Degree Connections Around Year of Death

Panel A: Coworkers' Total Earnings



Panel B: Coworkers' Labor Earnings

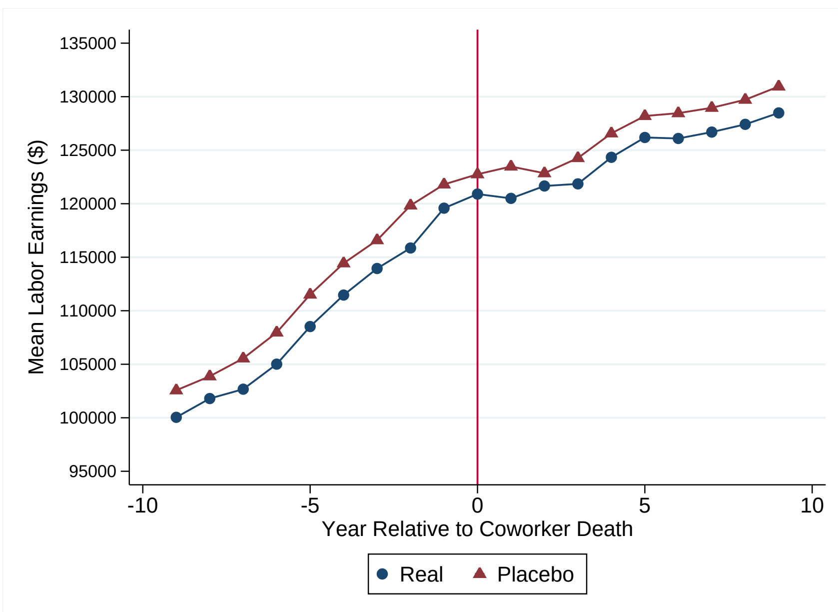
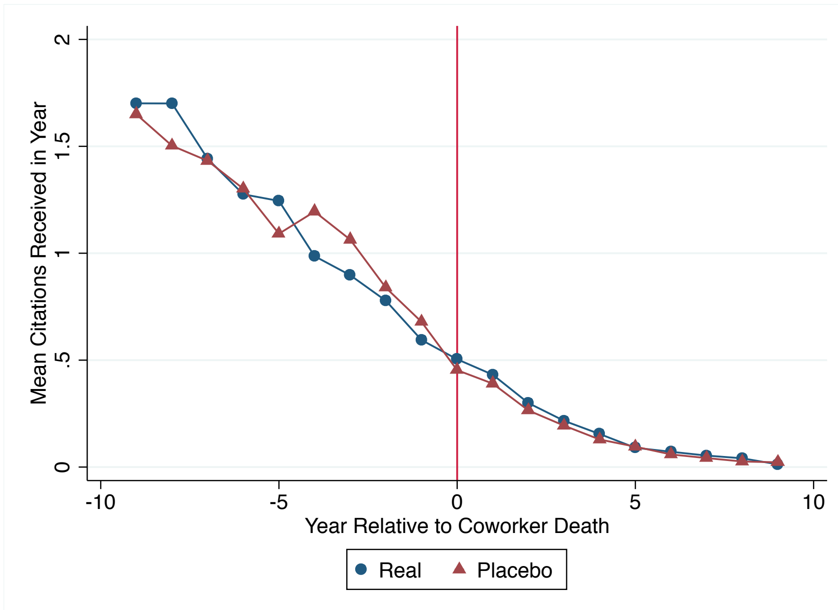


Figure 5: Path of Outcomes for Coworkers and Second-Degree Connections Around Year of Death *(continued)*

Panel C: Coworker's Adjusted Forward Citations Received for Patents Applied in Year



Panel D: Second-degree Connections' Total Earnings

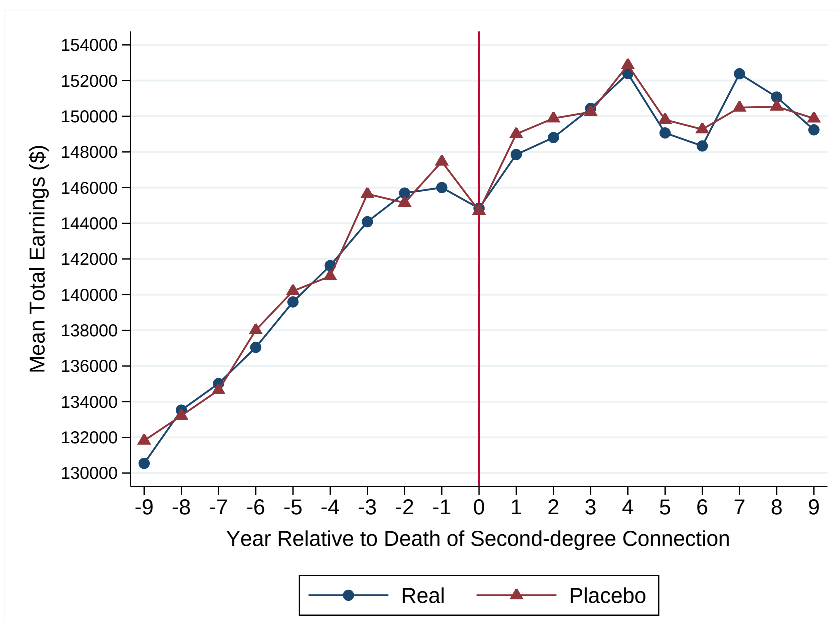
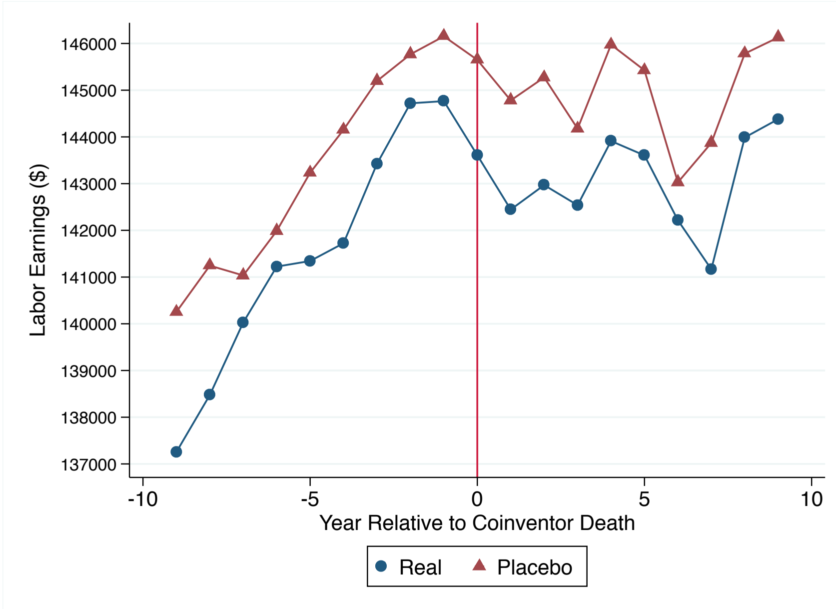
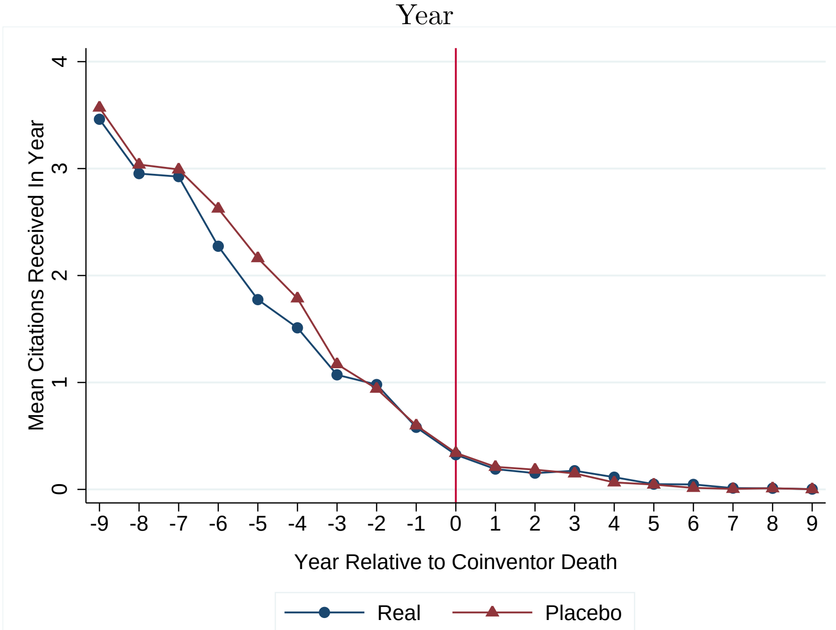


Figure 5: Path of Outcomes for Coworkers and Second-Degree Connections Around Year of Death *(continued)*

Panel E: Second-degree Connections' Labor Earnings



Panel F: Second-degree Connections' Adjusted Forward Citations Received for Patents Applied in Year



Notes: Panels A to F of this figure show the path of mean total earnings, labor earnings and citations for real and placebo coworkers as well as for real and placebo second-degree connections around the year of death of their associated deceased. The sample includes all real and placebo inventors in a 9-year window around the year of co-inventor death, i.e. inventor-year observations are dropped when the lead or lag relative to co-inventor death is above 9 years. The unbalanced nature of this panel is the same for real and placebo inventors. Dollar amounts are reported in 2012 dollars. Refer to section II.B for more details on the sample and to section II.C for more details on the outcome variables.

Table 3: Causal Effects of Inventor Death on Coworkers and Second-degree Connections

Panel A: Effect on Coworkers

	Total Earnings	Labor Earnings	Labor Earnings >0	Patent Count	Citation Count
$AfterDeath^{Real}$	207	236	0.00639**	0.0249*	0.0148**
s.e.	(571)	(582)	(0.00296)	(0.0131)	(0.00713)
$AfterDeath^{All}$	-745	-682	-0.00536**	-0.0366**	-0.00976**
s.e.	(818)	(853)	(0.00215)	(0.01664)	(0.00416)
Age and Year Fixed Effects	Yes	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	No	No
# Observations	335,708	335,708	335,708	335,708	335,708
# Coworkers	28,192	28,192	28,192	28,192	28,192
# Deceased	3,988	3,988	3,988	3,988	3,988
Estimator	OLS	OLS	OLS	Poisson	Poisson

Notes: This panel reports the estimated coefficients β^{Real} and β^{All} from specification (2) in the sample of coworkers. The five outcome variables are as follows: (1) total earnings; (2) labor earnings; (3) an indicator equal to one when the inventor receives a W-2, i.e. has positive labor earnings; (4) the number of patents the coworker applied for in a given year; (5) the number of forward citations received on patents that the coworker applied for in a given year (therefore, this variable reflects the timing and quality of patent applications by the survivor, not the timing of citations). Under the identification assumption described in Section III.B, β^{Real} gives the causal effect of coworker death on these various outcomes. Inventor-year observations are dropped when the lead or lag relative to co-inventor death is above 9 years. The unbalanced nature of this panel is the same for real and placebo inventors. Appendix Table C1 shows that the results are similar on coworker sample keeping firms of all sizes. Dollar amounts are reported in 2012 dollars. Standard errors are clustered around the deceased inventors. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Panel B: Effect on Second-degree Connections

	Total Earnings	Labor Earnings	Labor Earnings >0	Patent Count	Citation Count
$AfterDeath^{Real}$	-159	-9	0.0027	-0.00258	-0.02346
s.e.	(548)	(506)	(0.00325)	(0.02115)	(0.0210)
$AfterDeath^{All}$	-618	-684	-0.00618*	-0.08121**	-0.0208
s.e.	(749)	(565)	(0.00367)	(0.0363)	(0.02625)
Age and Year Fixed Effects	Yes	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	No	No
# Observations	265,421	265,421	265,421	265,421	265,421
# Second-degree Connections	23,331	23,331	23,331	23,331	23,331
# Deceased	4,183	4,183	4,183	4,183	4,183

Notes: This panel reports the estimated coefficients β^{Real} and β^{All} from specification (2) in the sample of second-degree connections. The five outcome variables are as in Panel A. Inventor-year observations are dropped when the lead or lag relative to co-inventor death is above 9 years. Dollar amounts are reported in 2012 dollars. Standard errors are clustered around the deceased inventors. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

For the second-degree connections, we find no statistically significant effect on any of the outcomes. The point estimates are close to zero and we can reject at the 5% confidence level any effect of a magnitude larger than one half of the effect documented for the direct co-inventors. This evidence provides a test of competing models of strategic interactions in networks. If the dominant force is a substitution effect as in Jackson and Wolinsky (1996), then we should find that the second-degree connections benefit from the death. But if strategic complementarities dominate as in Bramoulle et al. (2014), then the death should negatively affect the second-degree connections. Our finding that, on net, the effect on second-degree connections is negligible means that network effects are not first-order, as opposed to the direct impact on co-inventors.

Therefore, we can rule out firm disruption and network effects as primary mechanisms explaining the effect documented in Section III.[33] Moreover, the analysis of the effect on coworkers and second-degree connections generated new insights about the innovation production function: the results suggest that inventors within a firm are substitutable while there is no strong complementarity or substitutability patterns between inventors who are two nodes away in the co-invention network.[34]

IV.B Top-Down Spillovers Are Not the Driving Force

As documented in Section II, some teams are composed of inventors of similar age and compensation levels, while in others there are large gaps in age and compensation levels between team members. We study whether these patterns are important predictors of the heterogeneity in the average effects documented in Section III. In particular, we want to test whether the effect is driven by the death of "superstar" inventors or, more generally, by inventors of higher ability level than their associated survivors.

To do so, we repeat the estimation of the coefficient of interest, β^{Real}, by using specification (2) in different subsamples of the data. We partition the data depending on the quartile in which the total earnings of the (real and placebo) deceased and the (real and placebo) survivor inventors fall three years before the year of (real and placebo) death. The sample sizes in each subsample are

[33] We have also constructed a "citation network" of inventors who cited the deceased before their death but who were not among their direct co-inventors, second-degree connections or coworkers. We do not find evidence of statistically significant negative effects. These results are not surprising, given how diffuse citation networks are, but they establish that the effect is not driven by linkages in idea space. These results are available from the authors upon request.

[34] It is important to note that our quasi-experiment does not deliver insights about general substitution and complementarity patterns in the patent production function or in extended co-inventor networks. Indeed, the reduced-form effects we identify correspond to the idiosyncratic effect of an inventor on their coworkers and second-degree connections. It could be that the production function exhibits strong complementarities between coworkers, and yet that the causal effect of the premature death of an inventor's coworker on this inventor's earnings and patents is a precise zero, simply because this coworker can be replaced. Our analysis shows that co-inventors are a source of specific value for an inventor, in a way that coworkers and second-degree connections are not.

given in Appendix Table C2. This way of inferring relative ability levels can potentially create mean reversion patterns. For instance, it could be that survivor inventors who are in the first quartile of the earnings distribution three years before co-inventor death suffered from temporary shocks and that their earnings tend, on average, to increase afterwards. The use of our control group of placebo survivor inventors is sufficient to alleviate these concerns if the income processes are similar for the real and placebo survivor inventors prior to the death of the co-inventor (i.e. both groups are affected by mean reversion and other such patterns in similar ways). To investigate whether this is true, we examine the distribution of changes in total earnings for the years before the death of the co-inventor. The difference in this analysis relative to our earlier analysis in Section III is that we now want to ensure that the placebo survivor inventors are an appropriate control group for the distribution of changes in potential outcomes over time, not just for their mean. Table 4 shows that the distribution of earnings changes is very similar for the real and placebo survivor inventors.[35]

Table 4: Distribution of Annual Changes in Log Total Earnings Before Co-inventor Death

		Mean	SD	10pc	25pc	50pc	75pc	90pc
Total Earnings	Real Survivors	0.039	0.457	-0.0026	0.0169	0.035	0.0867	0.1436
	Placebo Survivors	0.040	0.461	-0.0024	0.0188	0.036	0.0844	0.1401

Notes: This table reports the distribution of year-to-year changes in log total earnings for real and placebo survivor inventors before the year of co-inventor death. The distributions are very similar across the two groups, suggesting that the income processes are similar for both groups and that the placebo inventors can be used as a control group for the analysis reported in Table 5. The results are similar when considering annual changes in the level of total earnings, the log of labor earnings and the level of labor earnings. For more details on the sample, see Section II.B.

Table 5 reports the results of this analysis. Consider for instance panel A on total earnings - the findings are similar for panel C, on labor learnings. This panel shows three main findings. First, the effect is significant and large in magnitude when the deceased and the survivor are in the same earnings quartile, i.e. are of similar seniority levels. This rejects the hypothesis that the effect documented in Section III is entirely driven by top-down spillovers from "superstar" inventors, because the effect persists for inventors of similar seniority levels. Second, holding constant the earnings quartile of the survivor, the effect is increasing in the earnings quartile of the deceased, showing that co-inventor of a higher seniority level are more difficult to substitute for. Third, the effect is not significant when the deceased is in a lower earnings quartile than the survivor. Although the point estimates are imprecisely estimated, it suggests that co-inventors of a lower

[35] We obtain similar results when considering changes of total earnings in levels as well as level or log changes for labor earnings.

seniority level are not a source of specific value for an inventor. The fact that lower ability team members suffer from the loss of higher ability team members, while in contrast higher ability team members are largely unaffected by the loss of a lower ability peer, could indicate that lower ability inventors extract "rents" from their collaboration with high ability co-inventors. However, this "rent" hypothesis cannot explain the large effect we find for team members of similar ability levels.

Moreover, panels C and D of Table 5 show that mechanical patterns (due to mean reversion or other statistical effects) play a very important role. These panels show that there are strong mean-reversion patterns: survivors in the lowest earnings quartile before (placebo) co-inventor death tend to perform better after the year of death, while survivors in the highest earnings quartile before (placebo) co-inventor death tend to perform worse after the year of death. Therefore, year, age and individual fixed effects are not sufficient to account for trends in earnings around the time of co-inventor death and it is important to include the $AfterDeath^{All}$ dummy introduced in specification (2).

We have conducted a series of robustness checks about these results. First, instead of running the analysis in different subsamples as in Table 5, we ran regressions with a linear interaction of the $AfterDeath$ indicator with the quartile difference or the level difference in the labor earnings levels of the survivor and the deceased, as well as with the age difference between the survivor and the deceased. Second, we have checked that the results are similar with other metrics of relative ability levels, namely the relative level of total earnings and the relative citation levels three years before death.[36] We find that the causal effect is larger when the survivor inventor is of lower ability or seniority than the deceased and the effect is still significant for inventors of equal ability or seniority levels.

[36] A limitation of using relative citations before death is that the survivor and the deceased have often co invented most of their patents together, therefore relative earnings appear to be a better signal of relative seniority.

Table 5: Heterogeneity in Effect by Relative Ability Levels of Co-Inventors

Panel A: Heterogeneity in the Causal Effect of Co-Inventor Death on Total Earnings

Deceased Earnings Quartile / Survivor Earnings Quartile	1	2	3	4
1	-2,652*	-1,301	1,298	902
s.e.	(1,553)	(1,328)	(1,680)	(1,081)
2	-3,573*	-2,798**	-810	-1,308
s.e.	(2,111)	(1,178)	(1,675)	(1,278)
3	-5,656**	-4,151**	-3,243**	-2,939
s.e.	(2,612)	(1,968)	(1,632)	(2,562)
4	-6,566*	-5,132**	-4,853*	-7,037**
s.e.	(3,450)	(2,530)	(2,650)	(3,256)

Notes: This panel reports the estimated coefficient β^{Real} from specification (2), with total earnings of the survivors as the outcome variable, in sixteen subsamples of the data. Each of these subsamples corresponds to a different combination of the total earnings quartiles of the survivor and the deceased. The earnings quartiles are computed three years before death and sample sizes for each subsample are given in Appendix Table C2. Under the identification assumption described in Section III.B, β^{Real} gives the causal effect of co-inventor death on total earnings. For instance, the panel shows that if the survivor and the deceased were both in the lowest quartile of total earnings three years before death, the causal effect of co-inventor death on the survivor was a decline of $2,652 in total earnings. Amounts are reported in 2012 dollars. Standard errors are clustered around the deceased inventors. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Panel B: Mean Reversion Patterns in Total Earnings Around Co-inventor Death

Deceased Earnings Quartile / Survivor Earnings Quartile	1	2	3	4
1	14,763***	3,373	-1,397	-18,977***
s.e.	(2,138)	(2,136)	(2,844)	(3,994)
2	14,493***	380	1,536	-13,665***
s.e.	(2,329)	(1,356)	(1,845)	(2,947)
3	15,237***	3,410**	1,087	-18,473***
s.e.	(2,401)	(1,425)	(2,200)	(3,803)
4	17,183***	-671	3,384	-13,539***
s.e.	(4,243)	(2,681)	(2,599)	(3,814)

Notes: This panel reports the estimated coefficient β^{All} from specification (2), with total earnings of the survivors as the outcome variable, in sixteen subsamples of the data. Each of these subsamples corresponds to a different combination of the total earnings quartiles of the survivor and the deceased. The earnings quartiles are computed three years before death and sample sizes for each subsample are given in Appendix Table C2. β^{All} gives the predictive effect of placebo co-inventor death on total earnings, conditional on year, age and individual fixed effects. For instance, the panel shows that if the placebo survivor and deceased were both in the lowest quartile of total earnings three years before death, then after the placebo death of their co-inventor, the total earnings of placebo survivor inventors tended to increase by $14,763. Amounts are reported in 2012 dollars. Standard errors are clustered around the deceased inventors. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 5: Heterogeneity in Effect by Relative Ability Levels of Co-Inventors *(continued)*

Panel C: Heterogeneity in the Causal Effect of Co-Inventor Death on Labor Earnings

Deceased Earnings Quartile / Survivor Earnings Quartile	1	2	3	4
1	-1,838**	801	15	-407
s.e.	(910)	(1,489)	(881)	(1,383)
2	-2,329*	-1,623**	-675	432
s.e.	(1,288)	(851)	(1,233)	(1,290)
3	-3,381**	-2,932**	-2,054*	-1,809
s.e.	(1,584)	(1,449)	(1,142)	(1,758)
4	-4,268***	-3,868***	-3,956***	-4,955**
s.e.	(1,652)	(1,302)	(1,476)	(2,007)

Notes: This panel reports the estimated coefficient β^{Real} from specification (2), with labor earnings of the survivors as the outcome variable, in sixteen subsamples of the data. Each of these subsamples corresponds to a different combination of the total earnings quartiles of the survivor and the deceased. The earnings quartiles are computed three years before death and sample sizes for each subsample are given in Appendix Table C2. Under the identification assumption described in Section III.B, β^{Real} gives the causal effect of co-inventor death on labor earnings. For instance, the panel shows that if the survivor and the deceased were both in the lowest quartile of total earnings three years before death, the causal effect of co-inventor death on the survivor was a decline of $1,838 in labor earnings. Amounts are reported in 2012 dollars. Standard errors are clustered around the deceased inventors. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Panel D: Mean Reversion Patterns in Labor Earnings Around Co-inventor Death

Deceased Earnings Quartile / Survivor Earnings Quartile	1	2	3	4
1	10,437***	-1,221	-2,107	-11,581***
s.e.	(1,699)	(1,359)	(2,093)	(3,391)
2	10,295***	1,046	-3,679**	-5,783*
s.e.	(1,591)	(905)	(1,456)	(3,354)
3	13,446***	964	-1,152	-6,895***
s.e.	(1,945)	(1,014)	(1,171)	(2,355)
4	19,292***	-1,697	-1,556	-6,576***
s.e.	(2,518)	(1,317)	(1,598)	(2,356)

Notes: This panel reports the estimated coefficient β^{All} from specification (2), with labor earnings of the survivors as the outcome variable, in sixteen subsamples of the data. Each of these subsamples corresponds to a different combination for the total earnings quartiles of the survivor and the deceased. The earnings quartiles are computed three years before death and sample sizes for each subsample are given in Appendix Table C2. β^{All} gives the predictive effect of placebo co-inventor death on total earnings, conditional on year, age and individual fixed effects. For instance, the panel shows that if the placebo survivor and deceased were both in the lowest quartile of total earnings three years before death, then after the placebo death of their co-inventor, the total earnings of placebo survivor inventors tended to increase by $10,437. Amounts are reported in 2012 dollars. Standard errors are clustered around the deceased inventors. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

IV.C The Effect Is Driven by Close-Knit Teams

We consider various measures of collaboration intensity between deceased and survivor inventors, which Table 6 shows vary widely in our sample: the number and share of patents the survivor inventor co-invented with the deceased, collaboration length (defined as the number of years between the first and last joint patent application between the survivor and the deceased), and collaboration recency (defined as the numbers of years between the death of the co-inventor and the application for the last co-invented patent with the survivor).

Table 6: Collaboration Patterns Between Deceased and Survivor Inventors Before Death

Variable	Sample	Mean	SD	10pc	25pc	50pc	75pc	90pc
# Patents	Real	8.114	17.285	1	1	3	9	18
	Placebo	7.41082	12.757	1	1	3	8	18
# Co-patents	Real	1.702	1.502	1	1	1	2	3
	Placebo	1.6108	1.394	1	1	1	2	3
Co-patent Share	Real	54.61	37.75	7.692	18.75	50	100	100
	Placebo	54.55	37.81	8.33	18.18	50	100	100
Collaboration Length	Real	0.8208	1.7393	0	0	0	1	3
	Placebo	0.7593	1.7050	0	0	0	1	3
Collaboration Recency	Real	6.1125	3.9756	1	3	6	9	12
	Placebo	5.673	4.0078	1	2	5	8	12
# Real Survivors	14,150							
# Placebo Survivors	13,350							

Notes: This table documents the heterogeneity in the intensity of collaboration between the deceased and survivor inventors in the years before (real or placebo) death. The variables are defined as follows: (1) # patents is the number of patents of the survivor before co-inventor death; (2) # co-patents is the number of patents co-invented by the survivor and the deceased before co-inventor death; (3) co-patent share is the share of the survivor's patents that were co-invented with the deceased before death; (4) collaboration length is the number of years that elapsed between the first and last joint patent application between the survivor and the deceased; (5) collaboration recency is the number of years that elapsed between the application year for the last patent co-invented by the survivor and the deceased and the year of co-inventor death. For more details on the sample, refer to Section II.B.

To examine whether heterogeneity in collaboration strength predicts heterogeneity in the causal effects, we set up the following specification:

$$Y_{it} = \begin{array}{c} \beta^{Real} AfterDeath_{it}^{Real} + \eta^{Real} X_i \cdot AfterDeath_{it}^{Real} + \beta^{All} AfterDeath_{it}^{All} + \\ \eta^{All} X_i \cdot AfterDeath_{it}^{All} + \sum_{j=25}^{70} \lambda_j 1_{\{age_{it}=j\}} + \sum_{m=1999}^{2012} \gamma_m 1_{\{t=m\}} + \alpha_i + \epsilon_{it} \end{array} \quad (3)$$

where X_i is a vector including all variables listed in Table 6, as well as the age of the survivor inventor at the time of death. The vector X_i is demeaned so that the point estimates for β^{Real} and β^{All} are left unaffected.

Table 7 reports the results for the relevant interaction terms. It shows that the various proxies for the intensity of the collaboration between the survivor inventor and the deceased (co-patent share, collaboration length and collaboration recency) are strong predictors of the magnitude of the causal effect of co-inventor death on the various outcomes. The point estimates are all negative and statistically significant. Using the standard deviations reported in Table 6 for the various regressors and the magnitude of the causal effects reported in Table 2, we can gauge the magnitude of the predictive effects. A one standard deviation increase in the share of copatents explains 75% of the average effect on total earnings, 78% of the average effect on labor earnings, 70% of the average effect on patent count and 54% of the average effect on citation count. Similarly, a one standard deviation increase in collaboration length explains 47% of the average effect on total earnings, 33% of the average effect on labor earnings, 46% of the average effect on patents and 53% of the average effect on citations. Lastly, a one standard deviation increase in collaboration recency explains 45% of the average effect on total earnings, 52% of the average effect of labor earnings, 22% of the average effect on patents and 21% of the average effect on citations. This indicates that the effect is driven by the loss of a co-inventor that the survivor was collaborating with extensively.[37]

Table 7: Heterogeneity in the Effect by Intensity of Collaboration Between Deceased and Survivor Inventors

η^{Real}	Total Earnings	Labor Earnings	Non-Labor Earnings	Patent Count	Citation Count
Co-patent Share	-75.132***	-56.669***	-17.236**	-0.00172**	-0.0013*
s.e.	(22.552)	(17.164)	(8.342)	(0.00085)	(0.00069)
Collaboration Length	-1,063.253***	-523.296**	-323.296***	-0.0245**	-0.02892*
s.e.	(405.382)	(228.55)	(118.516)	(0.01072)	(0.01537)
Collaboration Recency	447.921***	360.281***	110.728**	0.00508**	0.00482*
s.e.	(145.592)	(139.825)	(50.95)	(0.00256)	(0.00266)
# Co-patents	42.163	64.029	20.231	0.0015	0.00127
s.e.	(107.372)	(121.255)	(431.156)	(0.01962)	(0.0124)
# Patents	-49.129	5.022	-60.001	-0.00642**	-0.00442**
s.e.	(57.941)	(39.44)	(40.223)	(0.00287)	(0.00181)
Survivor's Age at Death	104.78*	40.961	50.899	- 0.00243**	-0.00323**
s.e.	(62.774)	(49.876)	(40.85)	(0.001073)	(0.00129)
Age and Year Fixed Effects	Yes	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	No	No
# Observations	325,726	325,726	325,726	325,726	325,726
# Survivors	27,500	27,500	27,500	27,500	27,500
# Deceased	9,428	9,428	9,428	9,428	9,428
Estimator	OLS	OLS	OLS	Poisson	Poisson

Notes: This table reports the estimated coefficients in the vectorη^{Real} from specification (3). The outcome variables reported in the five columns are total earnings, labor earnings, an indicator turning to one if the inventor receives a W2, the number of patents the survivor inventor applied for in a given year, and the number of forward citations received on patents that the survivor applied for in a given year (therefore, this variable reflects the timing and quality of patent applications by the survivor, not the timing of citations). The regressors are defined in the main text as well as in Table 6 and are demeaned so that the point estimates for the average causal effects are identical to Table 2. Standard errors are clustered around the deceased inventors. $*p < 0.1$, $** p < 0.05$, $*** p < 0.01$.

[37] Our results differ markedly from Azoulay et al. (2010), who do not find collaboration intensity to be predictive of the magnitude of the effect of the death of a superstar on their coauthors. It could be due to the fact that top-down spillovers, which are not the driving force in our data, do not strongly depend on the intensity of collaboration.

IV.D Team-Specific Capital as a Likely Mechanism

Taken together, the evidence suggests that the gradual decline in earnings and citations following the premature death of a co-inventor results from the fact that the survivor lost a partner with whom they were collaborating intensely. The heterogeneity in the effect by intensity of collaboration, as well as the pervasive nature of the effect across various kinds of teams, makes team-specific capital a likely mechanism. The difficulty of building a similar relationship with another inventor may result from high search costs or from the fact that the quality of the relationship improved endogenously over time, in response to relationship-specific investments made by each of the co-inventors.

Consistent with the team-specific capital interpretation, we find that the effect of co-inventor death is much larger in the context of joint production and exists across firm and geographic boundaries. First, we repeat the analysis of the effect of co-inventor death on the patents of the survivor, but now we only consider patents that were not co-invented with the deceased.[38] Table 8 reports that, for the various measures of patent production and citations, we consistently find a significant and negative effect of co-inventor death. Continued interaction with a co-inventor therefore benefits an inventor beyond co-inventions, which is consistent with the view of teams as a vehicle for knowledge transmission. However, the magnitude of the effect on the survivor's patents outside of patents with the deceased is much smaller (around -3%) relative to the effect on the total number of patents of the survivor documented in Table 2 (around -9%). This suggests that the main value of team-specific capital comes in the form of co-inventions and that the effect results from the fact that the survivor can no longer engage in joint projects with the deceased.[39]

Second, we show that the effect persists for inventors located in different firms and in different commuting zones. Panel A of Table 9 shows that the effect of co-inventor death on labor earnings is entirely driven by survivors who were in the same firm as the deceased at the time of death. In contrast, the second column shows that the effect of co-inventor death on non-labor earnings is similar regardless of whether or not the survivor and the deceased were in the same firm. Panel B of Table 9 shows a similar pattern based on the location of survivor and deceased inventors across commuting zones.[40] Therefore, team-specific capital is not tied to firm or geographic boundaries.

[38]Note that legal requirements impose that all inventors should be listed on a patent, otherwise the patent could be invalidated in court. We can therefore be confident that the patents that do no list the name of the deceased were indeed invented without the active collaboration of the deceased.

[39]Note that our results are very different from Azoulay *et al.* (2010), who find that the death of a "star" scientist causes a decline of similar magnitude in scientific publications with and without the deceased. In our setting, the importance of joint production between the deceased and the survivor is consistent with the gradual effect documented in Section III: innovation is a stochastic process and the placebo survivors gradually outperform the real survivors.

[40]These findings are consistent with the view that the effect of co-inventor death on earnings primarily comes from

Table 8: The Causal Effect of Co-inventor Death On the Survivor Beyond Joint Production

	Only Considering Patents that Were Not Co-invented With the Deceased			
	Patent Count	Citation Count	Count of Patents with No Citations	Count of Patents in Top 5% of Citations
$AfterDeath^{Real}$	-0.03088**	-0.03571**	-0.03288**	-0.0084*
s.e.	(0.01525)	(0.01815)	(0.01525)	(0.00478)
$AfterDeath^{All}$	0.1162**	0.08578	0.05763	0.0247
s.e.	(0.05319)	(0.12013)	(0.08136)	(0.02271)
Age and Year Fixed Effects	Yes	Yes	Yes	Yes
Individual Fixed Effects	No	No	No	No
# Observations	325,726	325,726	325,726	325,726
# Survivors	27,500	27,500	27,500	27,500
# Deceased	9,428	9,428	9,428	9,428
Estimator	Poisson	Poisson	Poisson	Poisson

Notes: This table reports the estimated coefficients β^{Real} and β^{All} from specification (2). The four outcome variables are as follows: (1) patent count is the number of patents the survivor inventor applied for in a given year, excluding all patents co-invented with the deceased; (2) citation count is the number of forward citations received on patents that the survivor applied for in a given year, excluding all patents co-invented with the deceased; (3) the count of patents with no citations is the number of patents that the survivor inventor applied for in a given year and that have never been cited as of December 2012, excluding all patents co-invented with the deceased; (4) the count of patents in the top 5% of citations is the number of patents the survivor inventor applied for in a given year that were in the top 5% of the citation distribution, excluding all patents co-invented with the deceased. The sample includes all real and placebo survivor inventors in a 9-year window around the year of co-inventor death, i.e. inventor-year observations are dropped when the lead or lag relative to co-inventor death is more than 9 years. The unbalanced nature of this panel is the same for real and placebo inventors. Standard errors are clustered around the deceased inventors. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

the fact that the survivor is no longer able to work with his co-inventor on joint inventions. Indeed, inventors who are co-inventors but who work for different firms may be collaborating on joint projects outside of their work as employees. If they are successful, these projects are likely to result in an increase in non-labor earnings rather than labor earnings.

Table 9: The Causal Effect of Co-inventor Death Across Firm and Geographic Boundaries

Panel A: Within and Across Firms

	Labor Earnings	Non-Labor Earnings	Patent Count	Citation Count
$AfterDeath^{Real}$	-113	-1,225**	-0.07071**	-0.07892**
s.e.	(964)	(583)	(0.03321)	(0.0353)
$AfterDeath^{Real} \cdot SameFirm$	-3,974***	122	-0.05928	-0.05123
s.e.	(1,465)	(983)	(0.06956)	(0.04326)
Age and Year Fixed Effects	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	Yes
# Observations	260,807	260,807	260,807	260,807
# Survivors	21,972	21,972	21,972	21,972
# Deceased	7,589	7,589	7,589	7,589
Estimator	OLS	OLS	Poisson	Poisson

Notes: This panel reports the estimated coefficients β^{Real} and $\widetilde{\beta^{Real}}$ from the following specification:

$$Y_{it} = \beta^{Real} AfterDeath_{it}^{Real} + \beta^{All} AfterDeath_{it}^{All} + \widetilde{\beta^{Real}} AfterDeath_{it}^{Real} \cdot SameFirm + \widetilde{\beta^{All}} AfterDeath_{it}^{All} \cdot SameFirm + \sum_{j=25}^{70} \lambda_j 1_{\{age_{it}=j\}} + \sum_{m=1999}^{2012} \gamma_m 1_{\{t=m\}} + \alpha_i + \epsilon_{it}$$

using similar notation to Section III.B and where $SameFirm$ is an indicator equal to one when the survivor and the deceased were in the same firm during the three years that preceded death. $SameFirm$ is equal to 0 when the survivor and the inventor were in different firms during the three years that preceded death. We exclude from the sample the survivor-deceased pairs that were not always in the same firm or always in a different firm during the three prior to death, or who were self-employed or unemployed, or for whom employment data is missing. 20.1% of the survivors are thus excluded. $SameFirm$ is equal to 1 for 46% of survivors in the sample. See Table 2 for details about the outcome variables. Standard errors are clustered around the deceased inventors. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Panel B: Within and Across Commuting Zones

	Labor Earnings	Non-Labor Earnings	Patent Count	Citation Count
$AfterDeath^{Real}$	-182	-1,411**	-0.09393***	-0.1229***
s.e.	(529)	(563)	(0.02901)	(0.02856)
$AfterDeath^{Real} \cdot SameCZ$	-4,049***	534	0.00093	0.0209
s.e.	(1,350)	(610)	(0.05512)	(0.0212)
Age and Year Fixed Effects	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	No	No
# Observations	292,752	292,752	292,752	292,752
# Survivors	24,686	24,686	24,686	24,686
# Deceased	8,579	8,579	8,579	8,579
Estimator	OLS	OLS	Poisson	Poisson

Notes: This panel reports the estimated coefficients β^{Real} and $\widetilde{\beta^{Real}}$ from the following specification:

$$Y_{it} = \beta^{Real} AfterDeath_{it}^{Real} + \beta^{All} AfterDeath_{it}^{All} + \widetilde{\beta^{Real}} AfterDeath_{it}^{Real} \cdot SameCZ + \widetilde{\beta^{All}} AfterDeath_{it}^{All} \cdot SameCZ + \sum_{j=25}^{70} \lambda_j 1_{\{age_{it}=j\}} + \sum_{m=1999}^{2012} \gamma_m 1_{\{t=m\}} + \alpha_i + \epsilon_{it}$$

using similar notation to Section III.B and where $SameCZ$ is an indicator variable equal to one when the survivor and the deceased were in the same commuting zone during the three years that preceded death. $SameCZ$ is equal to 0 when the survivor and the deceased were in different commuting zones during the three years that preceded death. We exclude from the sample the survivor-deceased pairs that were not always in the same commuting zone or always in a different commuting zone during the three years prior to death. 10.24% of the survivors are thus excluded. $SameCZ$ is equal to 1 for 55% of survivors in the sample. See Table 2 for details about the outcome variables. Standard errors are clustered around the deceased inventors. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

A number of mechanisms in which team-specific capital plays no role may be able to explain our results but appear unlikely. First, emotional distress following the loss of a co-inventor may result in a decline in productivity - however, for this mechanism to be consistent with the patterns we have documented, emotional distress would need to be long-lasting, it should be larger when losing a high-achieving peer and it should cause labor earnings to fall only for inventors who work in the same firm. Second, the effect of co-inventor death might be driven by disruption of current work - however, we find the effect to be long lasting and we also find an effect on the survivor inventor's patents beyond co-inventions with the deceased. Third, the effect could be driven by a change in physical inputs available to survivor inventors. For example, after the death of a prominent inventor, the R&D lab might close down, or the start up may fail - however, we find that the effect exists for inventors working in different firms, as well as for co-inventors of average ability, and we find no negative spillover effect on coworkers in the same firm as the deceased. Fourth, the effect may be driven by a lower ability inventor exploiting a rent from their collaboration with a higher ability deceased - however, the effect persists for co-inventors of equal ability levels and there is an effect beyond joint production, on the survivor's patents beyond co-inventions with the deceased.

Thus, our results show that team-specific capital is important in an inventor's career because it facilitates co-inventions and - to a lesser extent - knowledge transmission. We have conducted interviews with patent inventors to confirm that this mechanism is plausible.[41] Moreover, it is in line with the notion that playing a repeated game with team members helps curb moral hazard in joint production and information exchange (e.g. Stein, 2008). Appendix C documents other heterogeneity patterns in the effect of co-inventor death - by firm size, age, network size and survivor's citizenship status - which are of descriptive interest but are not statistically significant for most outcomes. We also document that co-inventor death does not have a strong impact on the probability that an inventor starts new collaborations or changes firms (except if the inventor was in a small firm before their co-inventor's death).

V Conclusion

In this paper, we have shown that team-specific capital is an important ingredient of the typical patent inventor's lifecycle earnings and productivity, much like firm-specific capital is crucial for the typical worker (Topel, 1991). Exploiting the premature deaths of 4,714 inventors in a difference-

[41]We spoke with fourteen inventors in small start-ups as well as large R&D labs in Silicon Valley. They pointed out the difficulty of building good collaborative relationships and emphasized the long-lasting nature of successful collaborations, which often continue to exist across firm boundaries.

in-differences research design, we find that a co-inventor's premature death causes a large and long-lasting decline in an inventor's labor earnings (- 3.8% after 8 years), total earnings (- 4% after 8 years) and citation-weighted patents (- 15% after 8 years). We find that this effect exists for various kinds of teams and is not limited to top-down spillovers within the team, although the effect is larger when the survivor inventor is of lower ability than the deceased inventor. Consistent with the team-specific capital interpretation, the effect is larger for more closely-knit teams and primarily applies to co-invention activities with the deceased.

The paper also provides estimates of the causal effect of an inventor's death on coworkers and second-degree connections. We find that an inventor's earnings and patents are not significantly adversely affected by the premature death of a coworker at the same firm who is not a co-inventor, nor by the premature death of an inventor two nodes away in the co-inventor network. This evidence indicates that inventors are not difficult to replace from the perspective of their coworkers and second-degree connections.

Identifying the magnitude and nature of spillover effects between inventors is central to innovation and tax policy design, because the impact of any policy may depend greatly not just on a given inventor's behavior but on a "multiplier effect" that affects the broader innovation process. Here, we have established empirically the relevance of team-specific capital, which generates a multiplier effect between co-inventors. This multiplier effect may cause a wedge between the private and social returns to the accumulation of team-specific capital. However, on its own our natural experiment cannot be used to conclude whether or not such a wedge exists (perhaps the employer internalizes all effects, or perhaps the mobility of inventors across both teams and firms creates a wedge between private and social returns). Furthermore, our evidence suggests that the social returns to improving the match technology between inventors may be very large. For instance, high-skill immigration policy might have a crucial role to play by increasing the supply of inventors (thus potentially reducing the fixed cost of finding a good match and making it easier for an inventor to find substitutes for their close collaborators) or by offering visa extensions to successful inventors (thus preserving team-specific capital that was built during the course of successful collaborations). Without further evidence on the exact mechanisms at play, however, the policy implications of our findings can only be tentative.

The evidence and methodology described in this paper point to several promising directions for future research. First, the parameters of a structural model of team-specific capital formation could be estimated by using the premature death shock, simulating the model with respect to such a shock and fitting moments in the data. Second, it would be useful to examine whether significant spillover effects exist in some subsamples of the more diffuse networks we have considered, given that these effects are more likely to be genuine externalities introducing a wedge between the private and social returns to knowledge production. Third, an important research direction is to uncover more about the nature of team-specific capital. In particular, is team-specific capital endogenously formed during the course of a collaboration or does it result from fixed costs incurred at the time of creation of the match? Finally, given the prevalence of teamwork in modern economies, investigating the role of team-specific capital in sectors of the economy beyond innovation and patents would be of great interest.

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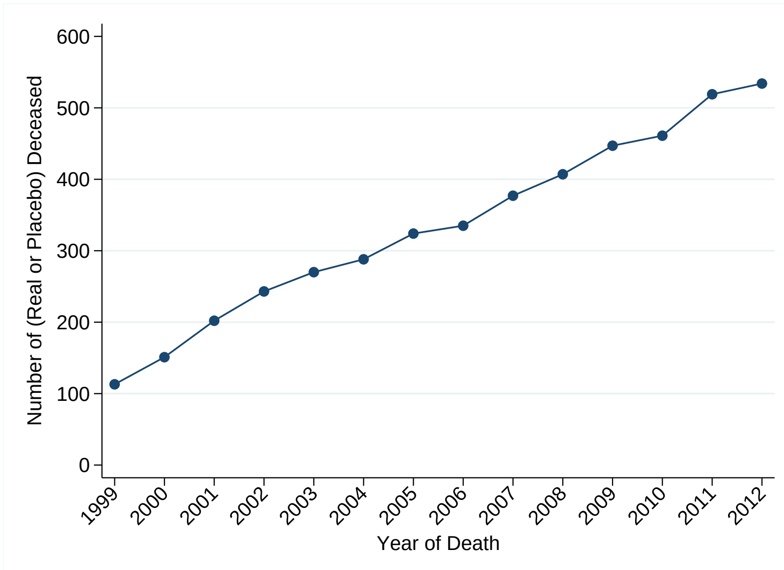
Appendix A

Additional Summary Statistics on Matched Inventors

Appendix Figure A1: Number of Deceased Inventors Per Year



Notes: This figure shows, in each year between 1999 and 2012, the number of inventors who passed away before the age of 60 and who had at least one co-inventor. The reason why the number of deceased inventors per year is increasing over time is that, for a deceased inventor to become part of our analysis, they need to have applied for at least one co-invented patent between 1996 and the year of their death (otherwise they have no associated survivor inventor). More and more inventors have applied for co-invented patents as we get closer to 2012, the end of our sample, therefore the number of deceased inventors per year is increasing over time.

Appendix Table A1: Balance in Technology Classes For Survivor Co-Inventors

	Share of Patents at Co-inventor Death	
Technology Class	Real	Placebo
1. Chemical	14.37	14.82
2. Computers & Communications	28.60	27.49
3. Drugs & Medical	15.05	14.50
4. Electrical & Electronic	14.99	15.39
5. Mechanical	13.20	13.82
6. Others	13.58	13.61

Notes: This table shows the breakdown by technology class of all patents the real and placebo survivor inventors had invented at the time of their co-inventor death. The table shows very good balance across the two groups, although we did not use this information for the match described in Section II.B.

Appendix Table A2: Additional Balance Tests

Variable	Sample	Mean	SD	10pc	25pc	50pc	75pc	90pc
	Real Survivors	9.726	10.85	2	3	6	12	21
Number of Co-inventors	Placebo Survivors	9.583	10.61	2	3	6	12	21
	Real Deceased	3.002	3.873	1	1	2	5	10
	Placebo Deceased	2.83199	3.423	1	1	2	5	9
	Real Survivors	35,191	124,097	44	300	4,400	29,200	69,500
Firm Size	Placebo Survivors	34,942	123,514	43	300	4,300	29,400	69,200
	Real Deceased	37,449	126,254	44	300	4,600	29,900	99,500
	Placebo Deceased	37,691	125,537	43	300	4,500	30,000	98,900
Year of	Real Survivors	2006.629	3.42	2002	2004	2006	2009	2011
Co-inventor Death	Placebo Survivors	2006.723	3.44	2002	2004	2006	2009	2011
	Real Deceased	4,714						
# Inventors	Placebo Deceased	4,714						
	Real Survivors	14,150						
	Placebo Survivors	13,350						

Notes: This table presents summary statistics computed for the real and placebo deceased and survivor inventors. The statistics on number of co-inventors and firm size are computed in the year of death. The distribution of firm size is based on all inventors who receive a W2. For both real and placebo survivor inventors, about 10% of inventor-year observations are missing a W2, i.e. the inventors have no labor earnings (either because they are unemployed, self-employed or retired). Firm size is rounded to the nearest one hundred to preserve taxpayer confidentiality.

Appendix Table A3: Summary Statistics for Real and Placebo Coworkers and Second-Degree Connections

Variable	Sample	Mean	SD	10pc	25pc	50pc	75pc	90pc
Total Earnings	Real Second-degree Connections	175,247	358,347	46,000	81,000	116,000	170,000	267,00
	Placebo Second-degree Connections	174,900	350,102	45,000	82,000	115,000	173,000	266,000
	Real Coworkers	149,861	312,721	39,000	64,000	115,000	169,000	251,000
	Placebo Coworkers	154,627	316,266	40,000	65,000	118,000	174,000	254,000
Labor Earnings	Real Second-degree Connections	144,449	291,697	39,000	70,00	108,000	156,00	239,000
	Placebo Second-degree Connections	146,674	297,697	40,000	72,00	110,000	159,000	241,000
	Real Coworkers	114,559	257,233	22,000	56,000	91,000	142,000	200,000
	Placebo Coworkers	117,691	258,908	25,000	57,000	94,000	146,000	204,000
Cumulative Applications	Real Second-degree Connections	10.42	42.78	1	2	5	11	25
	Placebo Second-degree Connections	9.92	25.21	1	2	5	11	25
	Real Coworkers	2.31	2.51	0	1	1	3	7
	Placebo Coworkers	2.50	2.43	0	1	1	3	7
Cumulative Citations	Real Second-degree Connections	37.76	170.11	0.35	1.2	7	26.5	80.34
	Placebo Second-degree Connections	39.40	173.23	0.22	1.1	7.5	29.5	83
	Real Coworkers	6.64	12.2	0	0	1	6.58	23.5
	Placebo Coworkers	8.74	13.09	0	0	3	10	29.13
Age	Real Second-degree Connections	47.72	19.08	34	40	47	55	63
	Placebo Second-degree Connections	47.93	19.96	35	39	47	55	64
	Real Coworkers	44.28	12.94	30	36	44	52	59
	Placebo Coworkers	44.49	16.13	30	36	44	52	59
# Inventors	Real Second-degree Connections	11,264						
	Placebo Second-degree Connections	12,047						
	Real Coworkers	13,828						
	Placebo Coworkers	14,364						

Notes: This table reports summary statistics for the various groups of inventors defined in Section II.B, using data between 1999 and 2012 before the year of death. The table shows that the real and placebo second-degree connections and the real and placebo coworkers are very similar prior to co-inventor death, although our matching strategy did not use any information on these inventors. Note that the real and placebo second-degree connections are very similar to the survivor inventors, while the distribution of outcomes for real and placebo coworkers is very similar to that of the full sample. Dollar amounts are reported in 2012 dollars and are rounded to the nearest $1,000 to preserve taxpayer confidentiality. The balance between real and placebo coworkers and second-degree connections is qualitatively similar when considering the exact percentile values. For a detailed description of the data sources and sample construction, see Sections II.A and II.B.

Table A4: Balance for Number of Real and Placebo Survivor Coworkers per Deceased (Full Sample)

Variable	Sample	Mean	SD	10pc	25pc	50pc	75pc	90pc
Number of Inventor Coworkers	Real	52.38	100.61	1	4	19	63	143
In The Year of Death	Placebo	46.75	93.85	1	4	19	65	141
# Real Coworkers	143,646							
# Placebo Coworkers	173,128							

Notes: This table reports the number of real and placebo coworkers per real and placebo deceased inventor. There is good balance except in the tail, which creates an imbalance in the total number of real and placebo survivor coworkers.

Appendix B

Robustness Checks on The Causal Effect of Co-inventor's Premature Death

F-Test for Pretrending

We can formally test the hypotheses that the point estimates obtained by running specification (1) and shown in Figure 3 are all the same before and after co-inventor death, considering an equal number of periods before and after co-inventor death:

$$H_0^{Before\ Death}:\ \beta_{-9}^{Real} = \beta_{-8}^{Real} = ... = \beta_{-2}^{Real}$$

$$H_0^{After\ Death}:\ \beta_{0}^{Real} = \beta_{2}^{Real} = ... = \beta_{7}^{Real}$$

The results of the F-tests, shown in Table 2, confirm that there is no pretrending while there is an effect after death. We can reject at the 10% confidence level that all coefficients are similar after death for adjusted gross income and labor earnings, but we cannot do so for non-labor earnings and citations, which are more noisily estimated (although the point estimates reported in Figure 2 appear very stable). We can never reject that the point estimates are all similar before death. Appendix Table B3 tests for dynamic effects by pulling together several lags after death, which reduces noise.

Appendix Table B1: Testing For Dynamic Effects, P-Values of F-Tests

	Total Earnings	Labor Earnings	Non-Labor Earnings	Citation Count
For $H_0^{Before\ Death}$	0.671	0.875	0.690	0.764
For $H_0^{After\ Death}$	0.079	0.084	0.268	0.382

Notes: This panel reports the p-values of F-tests for equality of the β_k^{Real} coefficients from specification (1) before and after death, as specified by the hypotheses $H_0^{Before\ Death}$ and $H_0^{After\ Death}$ described in the text above the table. For more details on the outcome variables and the sample, see Table 2 and the main text. P-values are adjusted for the clustering of standard errors around the deceased inventors. $^*p < 0.1$, $^{**}\ p < 0.05$, $^{***}\ p < 0.01$.

Balanced Panel

Appendix Table B2: Balanced Panel of Survivors Experiencing Co-inventor Death between 2003 and 2008

	Total Earnings	Labor Earnings	Labor Earnings >0	Patents Count	Citation Count
$AfterDeath^{Real}$	-2905.73**	-1907.36**	-0.0049*	-0.08090***	-0.0945***
s.e.	1345.88	806.25	0.00289	0.02957	0.0299
$AfterDeath^{All}$	199.025	-168.25	-0.00306**	-0.00622	-0.0293
s.e.	854.76	526.32	0.0021	0.02154	0.032
Age and Year Fixed Effects	Yes	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	No	No
# Observations	99,108	99,108	99,108	99,108	99,108
# Survivors	11,012	11,012	11,012	11,012	11,012
# Deceased	4,148	4,148	4,148	4,148	4,148
Estimator	OLS	OLS	OLS	Poisson	Poisson

Notes: This table reports the estimated coefficients β^{Real} and β^{All} from specification (2) on a balanced panel, keeping four years before and after death for each inventor in the sample. Specifically, we restrict the sample to survivor inventors whose associated deceased co-inventors passed away between 2003 and 2008 and we drop inventor-year observations when the lead or lag relative to co-inventor death is more than 4 years. Patent count is the number of patents the survivor inventor applied for in a given year, and citation count is the number of adjusted forward citations received on patents that the survivor applied for in a given year. Under the identification assumption described in Section III.B, β^{Real} gives the causal effect of co-inventor death on the various outcomes. The table shows that, for all outcome variables, we find a large and statistically significant effect. This indicates that the effect documented in Table 2 is not driven by the changing composition of the panel. The point estimates reported in this table are smaller than those reported in Table 2, because the balanced panel includes fewer inventor-year observations many years after death and Figure 3 shows that the negative effect on the survivors amplifies over time. Standard errors are clustered around the deceased inventors. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Dynamics

Appendix Table B3: Dynamic Causal Effect of Co-inventor Death, Full Sample

	Total Earnings	Labor Earnings	Labor Earnings >0	Patent Count	Citation Count
$AfterDeath^{Real}$	-2,081**	-1,735**	-0.00658**	-0.0743***	-0.0939***
s.e.	(853)	(683)	(0.002712)	(0.0258)	(0.0375)
$AfterDeath^{Real} \cdot LongRun$	-2,949**	-1,990**	-0.00576**	-0.0504**	-0.0507**
s.e.	(1,253)	(903)	(0.0026166)	0.0321	(0.0231)
Age and Year Fixed Effects	Yes	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	No	No
# Observations	325,726	325,726	325,726	325,726	325,726
# Survivors	27,500	27,500	27,500	27,500	27,500
# Deceased	9,428	9,428	9,428	9,428	9,428
Estimator	OLS	OLS	OLS	Poisson	Poisson

Notes: This panel reports the estimated coefficients β^{Real} and $\widetilde{\beta^{Real}}$ from the following specification:

$$Y_{it=} \begin{array}{c} \beta^{Real} AfterDeath_{it}^{Real} + \beta^{All} AfterDeath_{it}^{All} + \widetilde{\beta^{Real}} AfterDeath_{it}^{Real} \cdot LongRun + \widetilde{\beta^{All}} AfterDeath_{it}^{All} \cdot LongRun \\ + \sum_{j=25}^{70} \lambda_j 1_{\{age_{it}=j\}} + \sum_{m=1999}^{2012} \gamma_m 1_{\{t=m\}} + \alpha_i + \epsilon_{it} \end{array}$$

using similar notation to Section III.B and where *LongRun* is an indicator equal to one for observations more than four years after death. The columns report the results for total earnings, labor earnings, employment, the count of patents and the count of citations. For all outcome variables, we find that the effect in the long run is significantly larger than in the short run following death events. For more details on the sample see Table 2 and the main text. Standard errors are clustered around the deceased inventors. $*p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Appendix Table B4: Dynamic Causal Effect of Co-inventor Death, Sample Restricted to Deaths from 2003 to 2005

	Total Earnings	Labor Earnings	Labor Earnings >0	Patent Count	Citation Count
$AfterDeath^{Real}$	-1,980**	-1,635**	-0.00558*	-0.0843***	-0.0839**
s.e.	(990)	(823)	(0.003112)	(0.0311)	(0.0412)
$AfterDeath^{Real} \cdot LongRun$	-2,743**	-2,001*	-0.00549**	-0.0404*	-0.0443*
s.e.	(1,365)	(1,103)	(0.002724)	(0.02421)	(0.02634)
Age and Year Fixed Effects	Yes	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	No	No
# Observations	67,368	67,368	67,368	67,368	67,368
# Survivors	4,812	4,812	4,812	4,812	4,812
# Deceased	1,764	1,764	1,764	1,764	1,764
Estimator	OLS	OLS	OLS	Poisson	Poisson

Notes: This panel reports the estimated coefficients β^{Real} and $\widetilde{\beta^{Real}}$ from the following specification:

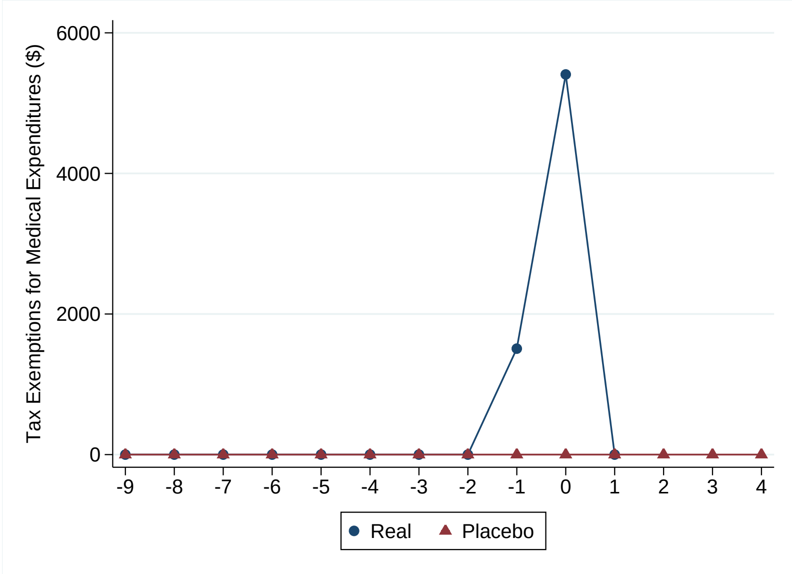
$$Y_{it=} \begin{array}{c} \beta^{Real} AfterDeath_{it}^{Real} + \beta^{All} AfterDeath_{it}^{All} + \widetilde{\beta^{Real}} AfterDeath_{it}^{Real} \cdot LongRun + \widetilde{\beta^{All}} AfterDeath_{it}^{All} \cdot LongRun \\ + \sum_{j=25}^{70} \lambda_j 1_{\{age_{it}=j\}} + \sum_{m=1999}^{2012} \gamma_m 1_{\{t=m\}} + \alpha_i + \epsilon_{it} \end{array}$$

using similar notation to Section III.B and where *LongRun* is an indicator equal to one for observations more than four years after death. The sample is restricted to the 4,812 co-inventors of the 1,764 real and placebo deceased with a year of death between 2003 and 2005. Inventor-year observations are dropped if the lag relative to co-inventor death is above seven years or if the lead relative to death is below four years. The various columns of the panel report the results for labor earnings, non-labor earnings, the count of patents and the count of citations. For all outcome variables, we find that the effect in the long run is significantly larger than in the short run following death events. The magnitude of the effects is similar to Figure 3 and Appendix Table B3, indicating that the dynamics of the effect are not driven by changes in the composition of the sample. Standard errors are clustered around the deceased inventors. $*p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

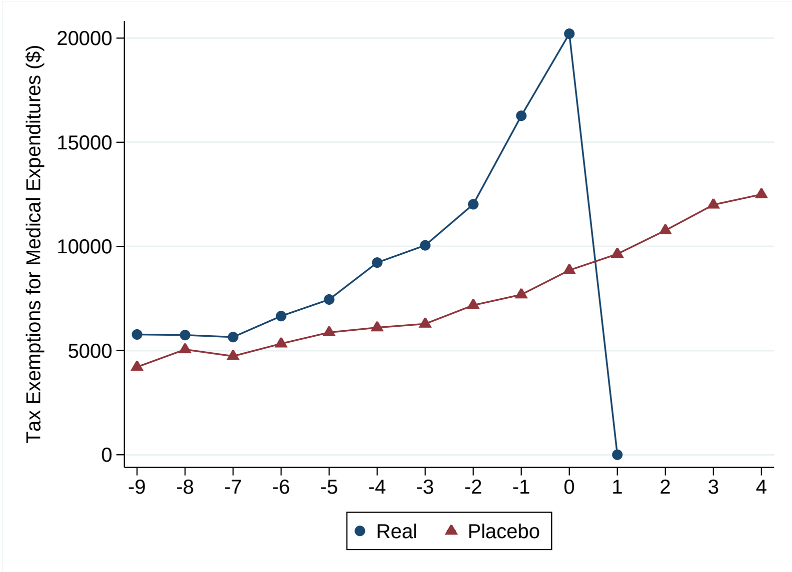
Anticipation

Appendix Figure B1: Tax Deductions for High Medical Expenditures Claimed by the Deceased

Panel A: 75th percentile



Panel B: 95th percentile



Notes: This figure shows the path of tax exemptions for medical expenditures claimed by the real and placebo deceased around the time of (real or placebo) death. For details on the sample, refer to Section II.B. Panel A shows that 75 percent of the real deceased inventors never claim any tax exemption for medical expenditures, except in the years just before death as well as during the year of death, suggesting that death is unanticipated for most survivors. Panel B shows that the 95th percentile of the distribution of tax deductions claimed for medical expenditures is very similar for real and placebo deceased until a few years before death, showing that some deaths result from lingering conditions and may therefore be anticipated.

Appendix Table B5: Results for Main Outcomes, Excluding Deceased who Claimed Any Tax Deduction for High Medical Expenditures

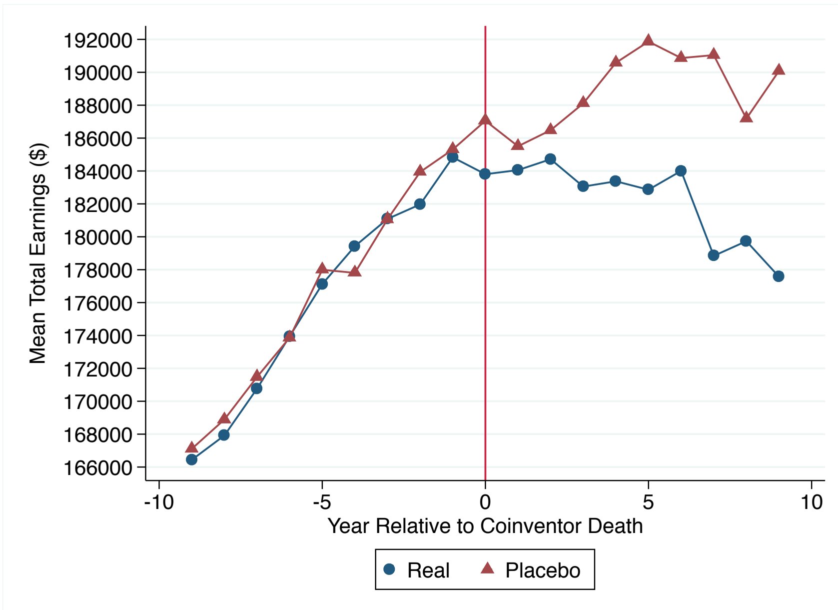
	Total Earnings	Labor Earnings	Labor Earnings >0	Patent Count	Citation Count
$AfterDeath^{Real}$	-4301.1562***	-3022.1***	-0.01047**	-0.1258***	-0.1017***
s.e.	1217.367	925.37	0.00417	0.0361	0.0442
$AfterDeath^{All}$	- 141.17	53.06	-0.00634**	-0.0020	0.0089
s.e.	576.10	595.30	0.0028	0.0231	0.00668
Age and Year Fixed Effects	Yes	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	No	No
# Observations	250,809	250,809	250,809	250,809	250,809
# Survivors	21,147	21,147	21,147	21,147	21,147
# Deceased	7,062	7,062	7,062	7,062	7,062
Estimator	OLS	OLS	OLS	Poisson	Poisson

Notes: This table reports the estimated coefficients β^{Real} and β^{All} from specification (2) in a sample that excludes all survivors whose associated deceased ever claimed tax deductions for medical expenditures. The table shows that the estimated causal effect of co-inventor death on the various outcomes is negative, statistically significant and large in magnitude. The point estimates are not very different but slightly larger than in Table 2. This result is not surprising, because our difference-in-differences estimator is biased downward if the causal effect of co-inventor impairement manifests itself before death. It bolsters the validity of the research design by showing that, if anything, we might be slightly underestimating the effect of co-inventor death due to lingering health conditions affecting some deceased inventors. Standard errors are clustered around the deceased inventors. $^*p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

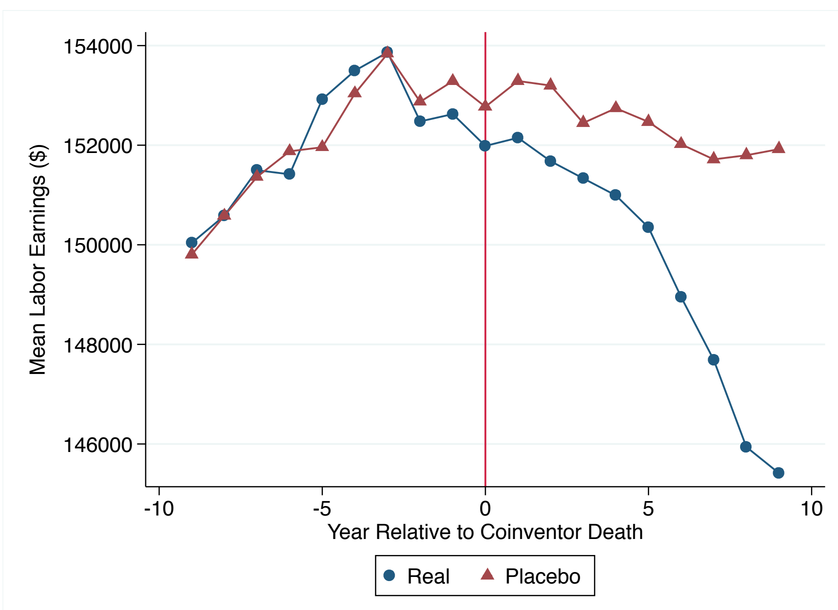
Alternative Matching Strategy

Appendix Figure B2: Path of Outcomes for Real and Placebo Survivor, Propensity Score Reweighting

Panel A: Survivor Inventors' Total Earnings

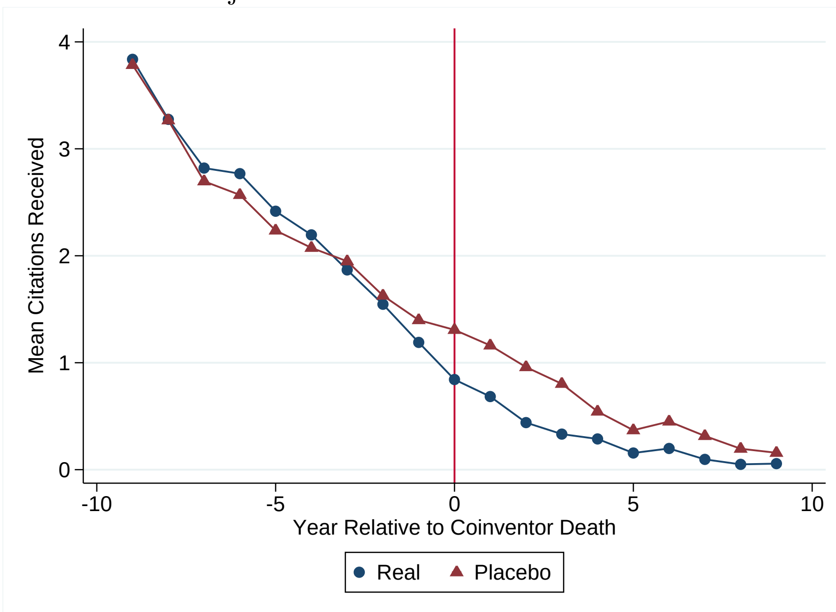


Panel B: Survivor Inventors' Labor Earnings



Appendix Figure B2: Path of Outcomes for Real and Placebo Survivor, Propensity Score Reweighting *(continued)*

Panel C: Survivor Inventor's Adjusted Forward Citations Received for Patents Applied in Year



Notes: Panels A to C of this figure show the path of mean total earnings, labor earnings and citations for real and placebo survivor inventors around the year of co-inventor death, where the placebo survivor inventors are reweighted on the propensity score, following the methodology described in the notes of Appendix Table B6. For all three outcomes, there is no pretrending and the real survivor inventors start performing worse relative to the placebo survivor inventors after the year of co-inventor death. The effect is large, gradual and sustained and is very similar to the results presented in Figure 2, indicating that the choice of matching strategy is not driving the results. The sample includes all real and placebo survivor inventors in a 9-year window around the year of co-inventor death, i.e. inventor-year observations are dropped when the lead or lag relative to co-inventor death is above 9 years. The unbalanced nature of this panel is the same for real and placebo inventors. Dollar amounts are reported in 2012 dollars. Refer to Section II.B for more details on the sample and to Section II.C for more details on the outcome variables.

Appendix Table B6: The Causal Effect of Co-Inventor Death, Reweighting on the Propensity Score

	Total Earnings	Labor Earnings	Labor Earnings >0	Non-Labor Earnings	Patent Count	Citation Count
$AfterDeath^{Real}$	-3,624***	-2,621***	-0.00945***	-1,032**	-0.0989***	-0.1103***
s.e.	(890)	(687)	(0.00289)	(472)	(0.0236)	(0.0266)
$AfterDeath^{All}$	- 322	-51	-0.0071**	552	-0.00081	0.07213
s.e.	(437)	(390)	(0.0036)	(278)	(0.01452)	(0.12341)
Age and Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	Yes	No	No
# Observations	734,742	734,742	734,742	734,742	734,742	734,742
# Deceased	24,929	24,929	24,929	24,929	24,929	24,929
Estimator	OLS	OLS	OLS	OLS	Poisson	Poisson

Notes: This panel reports the estimated coefficients β^{Real} and β^{All} from specification (2) in a sample of real and placebo survivors constructed following an alternative matching strategy, different from the one presented in the main text. Specifically, the matching strategy is as follows: (1) we identify all inventors who passed away before the age of 60 in our sample and we keep a random sample of 20,000 inventors who did not pass away during our sample ; (2) for each of the 20,000 inventors who did not pass away, we keep at random only one year of the sample, which will serve as our counterfactual year of death for these inventors in the following steps ; (3) we estimate the propensity score (which gives the probability of "treatment", i.e. the probability of passing away before the age of 60 between 1999 and 2012) by regressing an indicator for real deceased on age fixed effects, year of (real or placebo) death fixed effects, a fifth-order polynomial of wages in 1999, a fifth-order polynomial of total earnings in 1999, a fifth-order polynomial for cumulative patent applications at the time of death and a fifth-order polynomial for cumulative adjusted forward citations at the time of (real or placebo) death ; (4) we construct the co-inventor networks of all 24,929 real and placebo deceased in our sample for whom we have overlap in the propensity score ; (5) we run specification (2), which is described in the main text, in the sample of real and survivor inventor built in step (5) and using the propensity score estimated in step (2) as regression weight. The results reported in this table are very similar to the results reported in Table 2, showing that our results are robust to the choice of matching strategy. Note that the propensity-score reweighting strategy we employ here does not use any variable on the survivors, yet we find no pre-trending effects in Appendix Figure B2. Therefore, the details of the matching strategy do not matter for the substance of the results. It is important to use a matching strategy, however, because the real survivor inventors are in general older and of a higher level of achievement than the full sample of inventors, due to a selection effect (having a larger network of co-inventors increases the probability of experiencing the premature death of a co-inventor). For details about the outcome variables, refer to Table 2. Dollar amounts are reported in 2012 dollars. Standard errors are clustered around the deceased inventors. $^*p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Citations

Appendix Table B7: Other Citation Metrics

	3-Year Citation Count Around Grant Year	5-Year Citation Count Around Grant Year	5-Year Examiner-Added Citation Count Around Grant Year	5-Year Applicant-Added Citation Count Around Grant Year
$AfterDeath^{Real}$	-0.095***	-0.1242***	-0.0943***	-0.1448***
s.e.	(0.0245)	(0.0256)	(0.0342)	(0.0402)
$AfterDeath^{All}$	0.135	-0.0739	0.086	0.1528
s.e.	(0.1234)	(0.1345)	(0.1023)	(0.1234)
Age and Year Fixed Effects	Yes	Yes	Yes	Yes
Individual Fixed Effects	No	No	No	No
# Observations	325,726	325,726	325,726	325,726
# Survivors	27,500	27,500	27,500	27,500
# Deceased	9,428	9,428	9,428	9,428
Estimator	Poisson	Poisson	Poisson	Poisson

Notes: This table reports the estimated coefficients β^{Real} and β^{All} from specification (2), except that it does not include individual fixed effects because the Poisson estimator with individual fixed effects did not converge for several outcome variables. Appendix Table B8 shows that the results are similar with individual fixed effects, using a negative binomial estimator. The four outcome variables are as follows: (1) “3-year citation count around grant year” is the number of patents the survivor inventor applied for in a given year, weighted by the number of citations these patents received within three years of their respective year of grant; (2) “5-year citation count around grant year” is the number of patents the survivor inventor applied for in a given year, weighted by the number of citations these patents received within five years of their respective years of grant; (3) “5-year examiner-added citation count around grant year” is similar to the outcome variable in the second column, but taking into account only citations from patent examiners; (4) “5-year examiner-added citation count around grant year” is similar to the outcome variable in the second column, but taking into account only citations from applicants. For all outcome variables, we find a large and statistically significant effect. The magnitudes of these effects are similar to the effects reported in Table 2, Panel C, which shows the robustness of our result to the choice of the citation measure. For more details on the sample, see Table 2. Standard errors are clustered around the deceased inventors. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Appendix Table B8: Citation Results with Negative Binomial Estimator and Individual Fixed Effects

	3-Year Citation Count Around Grant Year	5-Year Citation Count Around Grant Year	5-Year Examiner-Added Citation Count Around Grant Year	5-Year Applicant-Added Citation Count Around Grant Year	Citation Count
$AfterDeath^{Real}$	-0.09508***	-0.1291***	-0.1122***	-0.09636***	-0.1299***
s.e.	0.0215	0.023	0.02172	0.0297	0.0299
$AfterDeath^{All}$	-0.1489***	-0.1691***	-0.161***	-0.1594***	-0.0445**
s.e.	0.04621	0.04221	0.05231	0.04267	0.0187
Age and Year Fixed Effects	Yes	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	Yes	Yes
# Observations	325,726	325,726	325,726	325,726	325,726
# Survivors	27,500	27,500	27,500	27,500	27,500
# Deceased	9,428	9,428	9,428	9,428	9,428
Estimator	Negative Binomial	Negative Binomial	Negative Binomial	Negative Binomial	Negative Binomial

Notes: This table reports the estimated coefficients β^{Real} and β^{All} from specification (2), using a negative binomial estimator. The five outcome variables are as follows: (1) "3-year citation count around grant year" is the number of patents the survivor inventor applied for in a given year, weighted by the number of citations these patents received within three years of their respective year of grant; (2) "5-year citation count around grant year" is the number of patents the survivor inventor applied for in a given year, weighted by the number of citations these patents received within five years of their respective years of grant; (3) "5-year examiner-added citation count around grant year" is similar to the outcome variable in the second column, but taking into account only citations added by patent examiners; (4) "5-year examiner-added citation count around grant year" is similar to the outcome variable in the second column, but taking into account only citations added by applicants; (5) citation count is the number of forward citations received on patents that the survivor applied for in a given year. For all outcome variables, we find a large and statistically significant effect. The magnitudes of these effects are similar to the effects reported in Table 2, Panel C, which shows the robustness of our results to the choice of estimator and the inclusion of individual fixed effects. For more details on the sample, see Table 2. Standard errors are clustered around the deceased inventors and computed by bootstrap with 100 draws. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Technology Classes

Appendix Table B9: Testing For Differences Across Technology Classes

	Total Earnings	Labor Earnings	Labor Earnings >0	Patents	Citations
$AfterDeath_{it}^{Real} \cdot Tech1$	-3,883*	-2,200*	-0.0075*	-0.07**	-0.1065**
s.e.	(2,273)	(1,135)	(0.0044)	(0.03005)	(0.04875)
$AfterDeath_{it}^{Real} \cdot Tech2$	-4,208**	-2,710**	-0.0096**	-0.140 ***	-0.1234***
s.e.	(2,054)	(1,319)	(0.0049)	(0.0440)	(0.0395)
$AfterDeath_{it}^{Real} \cdot Tech3$	-4,505*	-3,462***	-0.0063*	-0.092***	-0.1180***
s.e.	(2,364)	(1,333)	(0.0038)	(0.034)	(0.041)
$AfterDeath_{it}^{Real} \cdot Tech4$	-3,498**	-2,500*	-0.0117**	-0.10*	-0.0954*
s.e.	(1,613)	(1,331)	(0.00518)	(0.055)	(0.0500)
$AfterDeath_{it}^{Real} \cdot Tech5$	-3,080*	-2,075*	-0.00860*	-0.0692**	-0.0743*
s.e.	(1,740)	(1,102)	(0.00047)	(0.0343)	(0.0389)
$AfterDeath_{it}^{Real} \cdot Tech6$	-4,402*	-3,233**	-0.0048*	-0.064**	-0.072**
s.e.	(2,476)	(1,314)	(0.00294)	(0.0292)	(0.0312)
Age and Year Fixed Effects	Yes	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	No	No
F-Test on Equality of All β_{TechT}^{Real}	0.62	0.45	0.42	0.38	0.51
# Observations	325,726	325,726	325,726	325,726	325,726
# Survivors	27,500	27,500	27,500	27,500	27,500
# Deceased	9,428	9,428	9,428	9,428	9,428
Estimator	OLS	OLS	OLS	Poisson	Poisson

Notes: This panel reports the estimated coefficients $\beta_{Tech\ T}^{Real}$ from the following specification:

$$Y_{it} = \begin{array}{c} \beta^{Real} AfterDeath_{it}^{Real} + \beta^{All} \widetilde{AfterDeath}_{it}^{All} \\ + \sum_{T=1}^{6} \widetilde{\beta_{TechT}^{Real}} AfterDeath_{it}^{Real} \cdot TechT + \sum_{T=1}^{6} \widetilde{\beta_{TechT}^{All}} AfterDeath_{it}^{All} \cdot TechT \\ + \sum_{j=25}^{70} \lambda_j 1_{\{age_{it}=j\}} + \sum_{m=1999}^{2012} \gamma_m 1_{\{t=m\}} + \alpha_i + \epsilon_{it} \end{array}$$

using similar notation to Section III.B and where $Tech^T$ is an indicator equal to one when a survivor inventor has invented most of his patent prior to the year of co-inventor death in technology class T (we aggregate USPC classes into six main technology classes, as in Hall *et al.*, 2001). The distribution of real and placebo survivor inventors across the six main technology classes we consider is presented in Appendix Table A1. The point estimates show significant effects for all outcomes in all technology classes, indicating that our results are not driven by a particular technology class. Formally, for each outcome we report the p-value of a F-test for the hypothesis:

$$H_0 : \beta_{Tech1}^{Real} = \beta_{Tech2}^{Real} = ... = \beta_{Tech6}^{Real}$$

We fail to reject that the effect is the same across all technology classes. We have investigated the robustness of these results by running regressions in subsamples, considering in turns populations of survivor inventors specializing in each of the six technology classes before the year of co-inventor death. The results are qualitatively similar. For details on the sample, see Table 2. Standard errors are clustered around the deceased inventors and the p-values of F tests are adjusted accordingly. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Inference Accounting for the Matching Step

Appendix Table B10: Inference on The Causal Effect of Co-Inventor Death Accounting For the Matching Step

	Total Earnings	Labor Earnings	Labor Earnings >0	Non-Labor Earnings	Patents	Citations
$AfterDeath^{Real}$	-3,875***	-2,720***	-0.00914***	-1,199**	-0.0916***	-0.092***
s.e.	(839)	(659)	(0.00288)	(473)	(0.0178)	(0.0214)
$AfterDeath^{All}$	-215	-38	-0.0049**	652*	0.00055	0.0508
s.e.	(529)	(451)	(0.002)	(357)	0.01823	0.1161
Age and Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	Yes	Yes	No
# Observations	325,726	325,726	325,726	325,726	325,726	325,726
# Survivors	27,500	27,500	27,500	27,500	27,500	27,500
# Matched Pairs	4,714	4,714	4,714	4,714	4,714	4,714
Estimator	OLS	OLS	OLS	OLS	Poisson	Poisson

Notes: This table reports the estimated coefficients β^{Real} and β^{All} from specification (2). For details about the outcome variables and the sample, refer to Table 2. The difference between this table and Table 2 is that, here, standard errors are computed using the "coupled bootstrap" procedure presented in Abadie and Spiess (2015). We use one hundred bootstrap replications for each of the six outcome variables and we have checked that the results are similar when bootstrapping one thousand times for total earnings. The coupled bootstrap method applied to our setting works as follows: one redraws with replacement *pairs* of matched real-placebo deceased and all of their associated survivors (i.e. the full panel of observations for all of these survivors). The coupled bootstrap is effectively just a block bootstrap, but we re-sample together treated and matched control units, which reflects the dependency between treated and matched control units through the matched covariates (in our setting, the treated and matched control units are the real and placebo deceased). In contrast, in the standard bootstrap, treated and control units are treated as independent and are not resampled togethed. Note that the validity of the coupled bootstrap follows from a general result that applies to smooth functionals of the marginal outcome distributions, therefore it should be valid for inference on the difference-in-differences specification we run in our sample of real and placebo survivor inventors. The standard errors we obtain through this procedure are slightly smaller than the clustered standard errors reported in Table 2, which shows the robustness of our results. These smaller standard errors may result from a high positive correlation between the potential outcomes conditional on covariates, which is reasonable in our setting. Refer to Abadie and Spiess (2015) for more details.

Appendix C

Additional Results On Mechanisms

Causal Effect of Coworker Death in the Full Sample

Appendix Table C1: Causal Effect of Coworker Death, Including Coworkers in Firms of Any Size

	Total Earnings	Labor Earnings	Labor Earnings >0	Patent Count	Citation Count
β^{Real}	105.2	336.05	0.0034	0.0149	0.0048
s.e.	(461.22)	(312.59)	(0.0048)	(0.0110)	(0.0041)
β^{All}	-521	-702.5	-0.004357*	-0.03660**	-0.00623*
s.e.	(518)	(653)	(0.00241)	(0.01464)	(0.00356)
Age and Year Fixed Effects	Yes	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	No	No
# Observations	3,642,901	3,642,901	3,642,901	3,642,901	3,642,901
# Coworkers	316,774	316,774	316,774	316,774	316,774
# Deceased	6,289	6,289	6,289	6,289	6,289
Estimator	OLS	OLS	OLS	Poisson	Poisson

Notes: This panel reports the estimated coefficients β^{Real} and β^{All} from specification (2) for the sample of coworkers, considering deceased inventors in firms of any size. The five outcome variables are as follows: (1) total earnings; (2) labor earnings; (3) an indicator equal to one when the inventor receives a W-2, i.e. is employed; (4) the number of patents the coworker applied for in a given year; (5) the number of forward citations received on patents that the coworker applied for in a given year (therefore, this variable reflects the timing and quality of patent applications by the survivor, not the timing of citations). Under the identification assumption described in Section III.B, β^{Real} gives the causal effect of coworker death on these various outcomes. We do not find any significant effect for any of the outcomes, and the point estimates are positive. These results are qualitatively similar to those presented in Table 3: the absence of a negative effect on coworkers rules out the theory that the large effects documented in Section III are driven by the disruption of the firm. In contrast with Table 3, we no longer find positive and significant effects on the extensive margin of labor earnings, patents and citations, which could be because the firms we consider here are too large for any substitutability pattern to operate between inventor coworkers on average. Inventor-year observations are dropped when the lead or lag relative to coworker death is above 9 years. The unbalanced nature of this panel is the same for real and placebo coworkers. Dollar amounts are reported in 2012 dollars. Standard errors are clustered around the deceased inventors. $*p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Sample Sizes for Results by Relative Ability Levels

Appendix Table C2: Sample Sizes for Analysis by Relative Ability Levels

Deceased Earnings Quartile / Survivor Earnings Quartile	1	2	3	4
1	42,431 / 4,040 / 2,706	22,300 / 1,884 / 1,132	1,9619 / 1,706 / 1,062	17,251 / 1,456 / 887
2	20,968 / 1,747 / 1,150	37,390 / 3,382 / 1,625	28,158 / 2,485 / 1,349	17,476 / 1,506 / 975
3	20,085 / 1,685 / 989	15,899 / 1,366 / 617	20,465 / 1,686 / 711	11,696 / 1,071 / 549
4	9,132 / 825 / 354	11,090 / 981 / 379	11,540 / 1053 / 477	14,354 / 1,313 / 535

Notes: This panel reports the sample sizes for each of the sixteen subsamples studied in the various panels of Table 5. Each of these subsamples corresponds to a different combination for the total earnings quartiles of the survivor and the deceased. The earnings quartiles are computed three years before death. Within each cell, the sample sizes are reported according to the following format: Number of observations / Number of survivors / Number of deceased. For instance, in the subsample of survivor inventors who were in the lowest earnings quartile three years before death and whose associated deceased was also in the lowest earnings quartile at that time, we have 2,706 real and placebo deceased, 4,040 real and placebo survivors, and 42,432 inventor-year observations.

Probability of Changing Firm

Appendix Table C3: Causal Effect of Co-Inventor Death on the Probability of Changing Firm

	Changing Firm
$AfterDeath_{it}^{Real}$	-0.00124
s.e.	(0.00192)
$AfterDeath_{it}^{All} \cdot SmallFirm$	0.00798**
s.e.	(0.004016)
Age and Year Fixed Effects	Yes
Individual Fixed Effects	Yes
# Observations	266,087
# Survivors	22,740
# Deceased	8,382
Estimator	OLS

Notes: This panel reports the estimated coefficients β^{Real} and $\widetilde{\beta^{Real}}$ from the following specification:

$$ChangingFirm_{it} = \begin{array}{c} \beta^{Real} AfterDeath_{it}^{Real} + \beta^{All} AfterDeath_{it}^{All} \\ + \widetilde{\beta^{Real}} AfterDeath_{it}^{Real} \cdot SmallFirm + \widetilde{\beta^{All}} AfterDeath_{it}^{All} \cdot SmallFirm \\ + \sum_{j=25}^{70} \lambda_j 1_{\{age_{it}=j\}} + \sum_{m=1999}^{2012} \gamma_m 1_{\{t=m\}} + \alpha_i + \epsilon_{it} \end{array}$$

where (1) $ChangingFirm_{it}$ is an indicator variable equal to 1 if the deceased is employed in a different firm in year t compared with the year prior to co-inventor death; (2) $SmallFirm$ is an indicator equal to one if the survivor was in a firm with less than one hundred employee in the year prior to coinventor death; (3) the rest of the specification is similar to specification (2) in the main text. The table shows that in general co-inventor death does not have a statistically significant impact on an inventor's probability of changing firms. However, survivor inventors who are in a small firm are more likely to change firms after co-inventor death. This finding is consistent with the view that the survivor inventor may be looking for new co-inventors and may change firms to do so. Dollar amounts are reported in 2012 dollars. Standard errors are clustered around the deceased inventors. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Probability of Getting a New Co-inventor

Appendix Table C4: Causal Effect of Co-Inventor Death on the Probability of Getting a New Co-inventor

	New Co-Inventor In Year
β^{Real}	0.05899
s.e.	(0.067409)
β^{All}	-0.107534
s.e.	(0.060466)
Age and Year Fixed Effects	Yes
Individual Fixed Effects	Yes
# Observations	325,726
# Survivors	27,500
# Deceased	9,428
Estimator	OLS

Notes: This panel reports the estimated coefficients β^{Real} and β^{All} for specification (2), using as an outcome variable the number of new coinventors of the survivor in a given year. This variable is built using data on patent applications and counts the number of new co-inventors of the survivor in a given year, i.e. the number of inventors who apply for a patent with the survivor in this year and who had never applied for a patent with the survivor in any of the previous years. We find no statistically significant effect, and the point estimate is small in magnitude. This suggests that the survivor inventor is not able to find substitutes for the deceased co-inventor, which may explain the strength of the effect on the survivor's earnings and patents documented in Table 2. Note that the outcome variable in this table is not a perfect measure of changes in collaboration patterns, since it is based on patent applications, i.e. we can observe the new co-inventor only when a patent application is filed. This creates a censoring problem, which however is similar for treated and control inventors. The sample includes all real and placebo survivor inventors in a 9-year window around the year of co-inventor death, i.e. inventor-year observations are dropped when the lead or lag relative to co-inventor death is above 9 years. The unbalanced nature of this panel is the same for real and placebo inventors. Dollar amounts are reported in 2012 dollars. Standard errors are clustered around the deceased inventors. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Heterogeneity by Survivor's Age

Appendix Table C5: Heterogeneity in Causal Effect of Co-Inventor Death by Age Quartile

	Total Earnings	Labor Earnings	Labor Earnings >0	Patent Count	Citation Count
$AfterDeath^{Real}$	-3,484***	-2,526***	- 0.00476	-0.0978***	-0.1096***
s.e.	1,102	724	0.00312	0.02915	0.03451
$AfterDeath^{Real} \cdot AgeQ2$	33.8527	-218	0.000146	-0.00385	0.028
s.e.	549.83	412	0.000882	0.00461	0.0360
$AfterDeath^{Real} \cdot AgeQ3$	-990	-149	-0.00451**	0.001311	-0.001296
	950	567	0.00208	0.04823	0.003143
$AfterDeath^{Real} \cdot AgeQ4$	-1,533.1	-1,011.29	-0.00964***	-0.0498	-0.00535
	1,288.78	738	0.0035	0.02959	0.00371
Age and Year Fixed Effects	Yes	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	No	No
# Observations	325,726	325,726	325,726	325,726	325,726
# Survivors	27,500	27,500	27,500	27,500	27,500
# Deceased	9,428	9,428	9,428	9,428	9,428
Estimator	OLS	OLS	OLS	Poisson	Poisson

Notes: This panel reports the estimated coefficients β^{Real} and $\widetilde{\beta^{Real}_{Qk}}$ from the following specification:

$$Y_{it} = \beta^{Real} AfterDeath^{Real}_{it} + \beta^{All} AfterDeath^{All}_{it} + \sum_{k=2}^{4} \widetilde{\beta^{Real}_{Qk}} AfterDeath^{Real}_{it} \cdot AgeQk + \sum_{k=2}^{4} \widetilde{\beta^{All}} AfterDeath^{All}_{it} \cdot AgeQk + \sum_{j=25}^{70} \lambda_j 1_{\{age_{it}=j\}} + \sum_{m=1999}^{2012} \gamma_m 1_{\{t=m\}} + \alpha_i + \epsilon_{it}$$

using similar notation to Section III.B and where $AgeQk$ is an indicator equal to one when the survivor is in the k-th quartile of age at co-inventor death. The specification with the Poisson estimator for columns 4 and 5 of the table is similar. The table shows that there is no significant heterogeneity in the causal effect of co-inventor death on the various outcomes by age quartile, except on the extensive margin of labor earnings, where the effect is driven by survivors who were older at the time of co-inventor death. For younger survivor inventors, the point estimate for the effect on the extensive margin of labor earnings is an imprecisely estimated zero. The sample includes all real and placebo survivor inventors in a 9-year window around the year of co-inventor death, i.e. inventor-year observations are dropped when the lead or lag relative to co-inventor death is above 9 years. The unbalanced nature of this panel is the same for real and placebo inventors. Dollar amounts are reported in 2012 dollars. Standard errors are clustered around the deceased inventors. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Heterogeneity by Firm Size

Appendix Table C6: Heterogeneity in Causal Effect of Co-Inventor Death by Firm Size Quartile

	Total Earnings	Labor Earnings	Labor Earnings >0	Patent Count	Citation Count
$AfterDeath^{Real}$	-3506***	-2,537***	-0.00940**	-0.0989***	-0.1020 ***
s.e.	(878)	(690)	(0.00415)	(0.0245)	(0.0234)
$AfterDeath^{Real} \cdot FirmQ2$	-422	169	0.0008	0.0012	0.0023
s.e.	(633)	(587)	(0.00135)	(0.00923)	(0.0030)
$AfterDeath^{Real} \cdot FirmQ3$	-395	-365	-0.000340	-0.0123	0.0032
	(533)	(453)	(0.00216)	(0.0183)	(0.00902)
$AfterDeath^{Real} \cdot FirmQ4$	198	-204	-0.00223	0.00212	0.0182
	(643)	(346)	(0.00173)	(0.01630)	(0.01504)
Age and Year Fixed Effects	Yes	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	No	No
# Observations	284,707	284,707	284,707	284,707	284,707
# Survivors	23,925	23,925	23,925	23,925	23,925
# Deceased	8,768	8,768	8,768	8,768	8,768
Estimator	OLS	OLS	OLS	Poisson	Poisson

Notes: This panel reports the estimated coefficients β^{Real} and $\widetilde{\beta^{Real}_{Qk}}$ from the following specification:

$$Y_{it} =$$
$$\beta^{Real} AfterDeath^{Real}_{it} + \beta^{All} AfterDeath^{All}_{it} + \sum_{k=2}^{4} \widetilde{\beta^{Real}_{Qk}} AfterDeath^{Real}_{it} \cdot FirmQk + \sum_{k=2}^{4} \widetilde{\beta^{All}} AfterDeath^{All}_{it} \cdot FirmQk$$
$$+ \sum_{j=25}^{70} \lambda_j 1_{\{age_{it}=j\}} + \sum_{m=1999}^{2012} \gamma_m 1_{\{t=m\}} + \alpha_i + \epsilon_{it}$$

using similar notation to Section III.B and where $FirmQk$ is an indicator equal to one when the survivor is in the k-th quartile of firm size in the year of co-inventor death. The specification with the Poisson estimator for columns 4 and 5 of the table is similar. The table shows that there is no significant heterogeneity in the causal effect of co-inventor death on the various outcomes by firm quartile. The sample includes all real and placebo survivor inventors who received a W2 at the time of co-inventor death. Inventor-year observations are dropped when the lead or lag relative to co-inventor death is above 9 years. The unbalanced nature of this panel is the same for real and placebo inventors. Dollar amounts are reported in 2012 dollars. Standard errors are clustered around the deceased inventors. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Heterogeneity by Citizenship Status

Appendix Table C7: Heterogeneity in Causal Effect of Co-Inventor Death by Survivor's Citizenship Status

	Total Earnings	Labor Earnings	Labor Earnings¿0	Patent Count	Citation Count
$AfterDeath^{Real}$	-3,675***	-2,600***	-0.0982***	-0.0790 ***	-0.1050 ***
s.e.	(918)	(683)	(0.0328)	(0.02431)	(0.0271)
$AfterDeath^{Real} \cdot Foreigner$	-727	-506	0.0083	-0.0463 **	0.0263
s.e.	(663)	(421)	(0.00988)	(0.0214)	(0.0200)
Age and Year Fixed Effects	Yes	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	No	No
# Observations	325,726	325,726	325,726	325,726	325,726
# Survivors	27,500	27,500	27,500	27,500	27,500
# Deceased	9,428	9,428	9,428	9,428	9,428
Estimator	OLS	OLS	OLS	Poisson	Poisson

Notes: This panel reports the estimated coefficients β^{Real} and $\widetilde{\beta^{Real}}$ from the following specification:

$$Y_{it} = \begin{array}{c} \beta^{Real} AfterDeath^{Real}_{it} + \beta^{All} AfterDeath^{All}_{it} + \widetilde{\beta^{Real}} AfterDeath^{Real}_{it} \cdot Foreigner + \widetilde{\beta^{All}} AfterDeath^{All}_{it} \cdot Foreigner \\ + \sum_{j=25}^{70} \lambda_j 1_{\{age_{it}=j\}} + \sum_{m=1999}^{2012} \gamma_m 1_{\{t=m\}} + \alpha_i + \epsilon_{it} \end{array}$$

using similar notation to Section III.B and where $Foreigner$ is an indicator turning to one when the survivor inventor is not a US citizen. The table shows that there is no significant heterogeneity in the causal effect of co-inventor death by citizenship status, except for patent count. This result is consistent with the notion that it may be more difficult for foreign inventors to find new co-inventors, hence a stronger decline in citations, but at the same time they may not be rewarded for performance on the same basis as US inventors, explaining the absence of differential effect on earnings. The sample includes all real and placebo survivor inventors in a 9-year window around the year of co-inventor death, i.e. inventor-year observations are dropped when the lead or lag relative to co-inventor death is above 9 years. The unbalanced nature of this panel is the same for real and placebo inventors. Dollar amounts are reported in 2012 dollars. Standard errors are clustered around the deceased inventors. $^*p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Heterogeneity by Network Size

Appendix Table C8: Heterogeneity in Causal Effect of Co-Inventor Death by Survivor's Network Size

	Total Earnings	Labor Earnings	Labor Earnings¿ >0)	Patents	Citations	New Co-inventor
β^{Real}	-3,573***	-2,615***	-0.00956***	-0.0891***	-0.0952***	0.02399
s.e.	(850)	(706)	(0.00341)	(0.0237)	(0.0232)	0.06321
$\beta^{Real} \times Small\ Network$	-534.4	-283.32	0.00123	-0.005737	0.00672	0.08838
s.e.	(614)	(450.5)	(0.0023)	0.0102	(0.01918)	(0.0591)
Age and Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes	No	No	Yes
# Observations	325,726	325,726	325,726	325,726	325,726	325,726
# Survivors	27,500	27,500	27,500	27,500	27,500	27,500
# Deceased	9,428	9,428	9,428	9,428	9,428	9,428
Estimator	OLS	OLS	OLS	OLS	Poisson	OLS

Notes: This panel reports the estimated coefficients β^{Real} and $\widetilde{\beta^{Real}}$ from the following specification:

$$Y_{it} = \begin{array}{c} \beta^{Real} AfterDeath^{Real}_{it} + \beta^{All} AfterDeath^{All}_{it} \\ +\widetilde{\beta^{Real}} AfterDeath^{Real}_{it} \cdot SmallNetwork + \widetilde{\beta^{All}} AfterDeath^{All}_{it} \cdot SmallNetwork \\ + \sum_{j=25}^{70} \lambda_j 1_{\{age_{it}=j\}} + \sum_{m=1999}^{2012} \gamma_m 1_{\{t=m\}} + \alpha_i + \epsilon_{it} \end{array}$$

using similar notation to Section III.B and where *SmallNetwork* is an indicator turning to one when the size of the co-inventor network of the survivor inventor is below median at the time of death. The table shows that there is no significant heterogeneity in the causal effect of co-inventor death by network size. This result is qualitatively similar when considering other interaction terms (linear, quartile) based on survivor's network size at the time of death. An explanation for this finding is that the observed network of co-inventors at the time of death may be a noisy proxy for the survivor's actual network, given that collaborations are ongoing before patent applications are filed. Overall, the network size variable appears to be a less reliable indicator of the difficulty for the survivor to recover from the death of his co-inventor than the measures of collaboration intensity presented in Table 6. The sample includes all real and placebo survivor inventors in a 9-year window around the year of co-inventor death, i.e. inventor-year observations are dropped when the lead or lag relative to co-inventor death is above 9 years. The unbalanced nature of this panel is the same for real and placebo inventors. Dollar amounts are reported in 2012 dollars. Standard errors are clustered around the deceased inventors. *$p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Appendix D

Econometric Considerations

What is Identified In Specification (1)?

This appendix considers specification (1) introduced in Section III and asks what is identified about the coefficients $\{\beta^{Real}(k)\}$ and $\{\beta^{All}(k)\}$. k denotes the year relative to co-inventor death, which can be expressed as the difference between the time of co-inventor death (CDT_i) and time τ (so $k = \tau - CDT_i$). We delay imposing any "normalization" on the model and we note that $\forall \mu \in R$:

$$\begin{aligned}\beta^{All}(\tau - CDT_i) + \gamma(\tau) + \alpha(i) &= [\beta^{All}(\tau - CDT_i) - \mu(\tau - CDT_i)] + [\gamma(\tau) + \mu \cdot \tau] + [\alpha(i) - \mu \cdot CDT_i] \\ &= \widetilde{\beta^{All}}(\tau - CDT_i) + \widetilde{\gamma}(\tau) + \widetilde{\alpha}(i)\end{aligned}$$

Therefore, any function of the full vector coefficients, $G(\beta^{All}(.))$, is not identified unless $G(\beta^{All}(.) + h(.)) = G(\beta^{All}(.))$ for any linear function $h(k) = \alpha_1 + \alpha_2 k$. This observation helps understand which predictive effects are identified.[42] If $G(\beta^{All}, \gamma, \alpha)$ is identified, then we can evaluate it and we will get a well-defined predicted value. In specification (1), any solution to the least-squares fit gives the same value for $G(\beta^{All}, \gamma, \alpha)$. Although the solution of the least-square fit in specification (1) is not unique because the regressor matrix does not have full column rank, there is a unique predicted value.

The intuition for this result is that the set of leads and lags associated with $\beta^{All}(k)$ applies to all individuals in the sample. As a result, when we first-difference the data to eliminate the individual fixed effects, we lose information about a linear trend that could affect all individuals either through the $\beta^{All}(k)$ coefficients or through the year or age fixed effects. So $\beta^{All}(k)$, the age fixed effects and the year fixed effects are identified only up to a linear time trend. In practice, when estimating specification (1), we can drop any two dummies within the set of age or year with fixed effects or within the set of leads and lags $\beta^{All}(k)$. This will serve as our "normalization" for the linear trend.

In contrast, $\beta^{Real}(k)$ is associated with a set of leads and lags that can turn to one only for the real survivors. As a result, $\beta^{Real}(k)$ is identified up to a level shift affecting all coefficients. Due to

[42] The point of a "normalization" is that imposing it will not affect the value of a predictive effect that is identified: to be identified means identified without any normalization.

the individual fixed effects, one of the $\beta^{Real}(k)$ must be normalized to zero, as is usually the case in estimators with a full set of leads and lags around an event.

Empirical Relevance

Our specifications (1) and (2) are an application of the standard difference-in-differences estimator to our setting. The current practice in the literature with a setting similar to ours, for instance Azoulay *et al.* (2010) and Oettl (2012), is to use specifications including age, year and individual fixed effects only, without including L_{it}^{All} (as in specification (1)) or $AfterDeath_{it}^{All}$ (as in specification (2)). Becker and Hvide (2013) present a specification similar to our specification (2), but appropriately testing for pre-trending requires using specification (1), as we do.

The point that age, year and individual fixed effects may not fully account for trends in life-time earnings and patents around co-inventor death is a simple but crucial one. Had we not included $AfterDeath_{it}^{All}$ in specification (2), we would have over-estimated the effect of co-inventor death on the probability of being employed by 50% (Table 2, Panel B), we would have spuriously concluded that an inventor death causes a decline in the patents and in the probability of being employed of this inventor's coworkers and second-degree connections (Table 3, Panels A and B), and we would have mistaken mean-reversion patterns for heterogeneity in the causal effect of co-inventor death by relative ability level of the survivor and the deceased (Table 5, Panels B and C).

Appendix E

Data Appendix

This section documents the most important steps for the construction of the matched inventor-taxpayer database from Bell et al. (2015), provides a comparison of the distribution of Census firm size and EIN size, and gives summary statistics on the composition of patent inventor teams.

A. Data Construction

A.1 Data Preparation

- **Suffix Standardization**. Suffixes may appear at the end of taxpayers' first, middle, or last name fields. Any time any of these fields ends with a space followed by "JR", "SR", or a numeral I-IV, the suffix is stripped out and stored separately from the name[43].
- **First name to imputed first/middle name**. The USPTO separates inventor names into "first" and "last," but the Treasury administrative tax files often separate names into first, middle, and last. In practice, many inventors do include a middle initial or name in the first name field. Whenever there is a single space in the inventor's first name field, for the purposes of matching, we allow the first string to be an imputed first name, and the second string to be an imputed middle name or initial. The use of these imputed names is outlined below.

A.2 Pseudo code for Match on Name and Location

The exact matching stages are as follows. We conduct seven progressive rounds of matching. Inventors enter a match round only if they have not already been matched to a taxpayer in an earlier round. Each round consists of a name criterion and a location criterion. The share of data matched in each round is noted, with an impressive 49% being exact matches on the first stage.

- The matching algorithm takes as input a relation of inventor data and five relations of Treasury administrative tax files:
  - Input relations:
    - Inventors(inv_id, first, last, imputed_first, imputed_middle, suffix) - directly from USPTO

[43] Numerals I and V are only permissive suffixes at the end of a last name field, as these may be middle initials in a middle name field.

    * NamesW2(irs_id, first, middle, last, suffix) - all names used by individual on W2 information returns; name field is recorded as first, middle, and last
    * Names1040(irs_id, first, middle, last) - all self-reported names from 1040 forms[44]
    * Nameln1W2(irs_id, fullname) - all names from W2, but a separate variable not recorded as first, middle, last that was more frequently present
    * CitiesW2(irs_id, city, state) - all cities reported on W2
    * Zips1040(irs_id, name) - all zip codes reported on 1040
  - Output relation:
    * Unique-Matches (inv_id, irs_id)

- **Stage 1**: Exact match on name and location.
  - Name match: The inventor's last name exactly matches the taxpayer's last name. Either the inventor's first name field exactly matches the concatenation of the Treasury administrative tax files first and middle name fields or the Treasury administrative tax files middle name field is missing, but the first name fields match. If an imputed middle name is available for the inventor, candidate matches are removed if they have ever appeared in Treasury administrative tax files with a middle name or initial that conflicts with the inventor's.
  - Location match: The inventor's city and state must match some city and state reported by that taxpayer exactly.
  - 49% of patents are uniquely matched in this stage.

- **Stage 2**: Exact match on imputed name data and location.
  - Name match: The inventor's last name exactly matches the taxpayer's last name and the taxpayer's last name is the same as the inventor's imputed first name. Either the inventor's imputed middle name/initial matches one of the taxpayer's middle/initial name fields, or one of the two is missing. For inventors with non-missing imputed middle names, priority is given to matches to correct taxpayer middle names rather than to taxpayers with missing middle names. As above, candidate matches are removed if they

[44] We only take names off of 1040s for those who file singly because it proved difficult to parse names of those list them jointly

have ever appeared in Treasury administrative tax files with a conflicting middle name or initial.

– Location match: As above, the inventor's city and state must match some city and state reported by that taxpayer exactly.

– 12% of patents are uniquely matched in this stage.

- **Stage 3**: Exact match on actual or imputed name data and 1040 zip cross-walked.

  – Name match: The inventor's last name exactly matches the taxpayer's last name. The inventor's first name matches the taxpayer's first name in one of the following situations, in order of priority:

  1. Inventor's firstname is the same as the taxpayer's combined first and middle name.
  2. Inventor's imputed firstname matches taxpayer's and middle names match on initials.
  3. The inventor has no middlename data, but inventor's firstname is the same as the taxpayer's middle name.

  – As always, taxpayers are removed if they are ever observed filing with middle names in conflict with the inventor's.

  – Location match: The inventor's city and state match one of the city/state fields associated with one of the taxpayer's 1040 zip codes.

  – 3% of patents are uniquely matched in this stage.

- **Stage 4**: Same as previous stage, but using 1040 names instead of names from W2's.

  – Name match: The inventor's name matches the name of a 1040 (or matches without inventor's middle initial/name, and no taxpayer middle initials/names conflict with inventor's).

  – Location match: The inventor's city and state must match some city and state reported by that taxpayer exactly.

  – 6% of patents are uniquely matched in this stage.

- **Stage 5**: Match using W2 full name field.

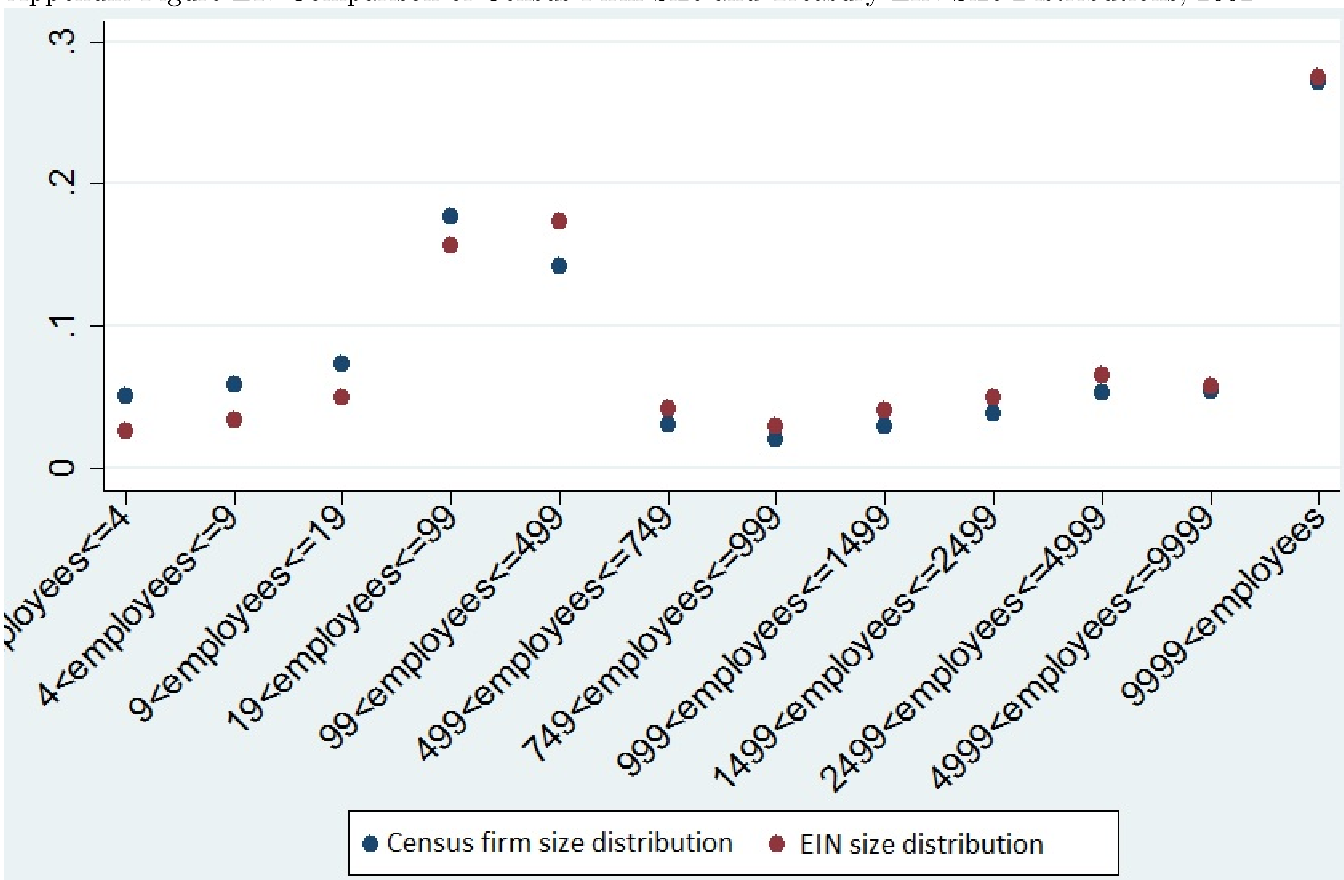
  - Name match: The inventor's FULL name exactly matches the FULL name of a taxpayer on a W2.
  - Location match: The inventor's city and state match one of the city/state fields associated with one of the taxpayer's 1040 zip codes.
  - 8% of patents are uniquely matched in this stage.

- **Stage 6**: Relaxed match using W2 full name field.
  - Name match: The inventor's full name (minus the imputed middle name) exactly matches the full name of a taxpayer on a W2.
  - Location match: The inventor's city and state match one of the city/state fields associated with one of the taxpayer's 1040 zip codes.
  - 1% of patents are uniquely matched in this stage.

- **Stage 7**: Match to all information returns.
  - Name match: The inventor's full name exactly matches the full name of a taxpayer on any type of information return form.
  - Location match: The inventor's city and state match one of the city/state fields associated with one of the taxpayer's information return forms.
  - 6% of patents are uniquely matched in this stage.

B. A Comparison of the Firm Size Distribution in Census Data and EIN Size Distribution in Treasury Administrative Tax Files

Appendix Figure E1: Comparison of Census Firm Size and Treasury EIN Size Distributions, 2002



Notes: This figure shows the distribution of firm size in the Census distribution and EIN size in Treasury tax files, based on 2002 data. The distributions are very similar.

C. More Summary Statistics on Patent Inventor Teams

Appendix Table E1: Distribution of Outcomes for Two-Inventor Teams in 2002 (N=23,210)

		Age Quantile of Oldest Team Member				
		1	2	3	4	5
	1	56	13	11	11	9
Age Quantile	2		16	31	30	21
of Youngest Team Member	3			21	43	34
	4				40	60
	5					100

		Labor Earnings Quantile of Richest Team Member				
		1	2	3	4	5
	1	24	26	24	12	14
Labor Earnings Quantile	2		26	44	16	14
of Poorest Team Member	3			36	35	28
	4				37	63
	5					100

		Adjusted Gross Income Quantile of Richest Team Member				
		1	2	3	4	5
	1	17	33	23	9	17
Adjusted Gross Income Quantile	2		20	45	14	19
of Poorest Team Member	3			34	28	38
	4				26	73
	5					100

Notes: The numbers indicate the percentage of teams in each quantile bin, expressed as a share of all teams with their poorest/youngest team member in the same quantile. See Figure 1 in Section II of the paper for more details about the sample.

Table E2: 10 Most Frequent Age Distributions in Teams of Two Inventors

Age Deciles										Frequency
1	2	3	4	5	6	7	8	9	10	
0	0	0	0	0	0	0	0	1	1	10,364
1	0	1	0	0	0	0	0	0	0	9,284
0	1	1	0	0	0	0	0	0	0	9,012
0	0	1	0	1	0	0	0	0	0	8,960
0	0	0	0	0	0	0	1	1	0	8,788
0	0	0	0	0	0	0	1	0	1	8,754
0	0	0	0	0	0	0	0	0	2	8,728
1	1	0	0	0	0	0	0	0	0	8,706
0	0	0	0	0	0	1	1	0	0	8,604
0	0	1	1	0	0	0	0	0	0	8,498

Notes: This table shows the most frequent age distributions in all teams of two inventors in our dataset. The age deciles are computed on the entire sample, as reported in Table 1 in the paper. For example, the table reports that 10,364 two-inventor teams had one inventor in the 9th decile of the age distribution and another in the 10th deciles. This is the most frequent age distribution in teams of two inventors in our sample. The sample includes 262,198 teams and the most frequent age distributions reported in this table represent 25% of the data.

Table E3: Frequency of Large Age Differences in Teams of Two Inventors

Age spread is at least X deciles	Share
4	46.5%
5	33.1%
6	22.5%
7	14.5%
8	8.5%
9	4.0%
10	1.3%

Notes: This table shows the percentage of teams of two inventors in our data for which the age spread between the two inventors is larger than 4, 5, 6, 7, 8, 9 or 10 deciles of the age distribution. The age deciles are computed on the entire sample, as reported in Table 1 in the paper. For example, the table reports that in 33.1% of teams, the age difference between the two inventors is larger than five age deciles. The sample includes 262,198 teams of two inventors.

Table E4: 10 Most Frequent Wage Distributions, Teams of Two Inventors

1	2	3	4	5	6	7	8	9	10	Frequency
0	0	0	0	0	0	0	0	1	1	8,129
0	1	1	0	0	0	0	0	0	0	7,385
0	0	0	0	0	0	0	0	0	2	7,365
0	0	0	0	0	0	0	1	1	0	7,272
0	0	0	0	0	0	1	1	0	0	6,739
1	1	0	0	0	0	0	0	0	0	6,697
0	0	1	1	0	0	0	0	0	0	6,614
0	0	0	0	1	1	0	0	0	0	6,246
0	0	0	0	0	0	1	0	1	0	6,163
0	0	0	0	0	0	0	1	0	1	6,096

Notes: This table shows the most frequent wage distributions in all teams of two inventors in our dataset. The wage deciles are computed on the entire sample, as reported in Table 1 in the paper. For example, the table reports that 8,129 two-inventor teams had one inventor in the 9th decile of the age distribution and another in the 10th deciles. This is the most frequent wage distribution in teams of two inventors in our sample. The sample includes 262,198 teams and the most frequent wage distributions reported in this table represent 26% of the data.

Table E5: Frequency of Large Wage Differences in Teams of Two Inventors

Wage spread is at least X deciles	Share
2	83%
3	59%
4	42%
5	29%
6	19%
7	12%
8	7%
9	3.5%
10	1.2%

Notes: This table shows the percentage of teams of two inventors in our data for which the wage spread between the two inventors is larger than 2, 3, 4, 5, 6, 7, 8, 9 or 10 deciles of the wage distribution. The wage deciles are computed on the entire sample, as reported in Table 1 in the paper. For example, the table reports that in 29% of teams, the wage difference between the two inventors is larger than five wage deciles. The sample includes 262,198 teams of two inventors.

Table E6: Frequency of Collaborations Across EINs

Team Size	N	Share w/ 1 EINs	Share w/ 2 EINs	Share w/ 3 EINs	Share w/ 4 EINs	Share w/ 5 EINs
2	262,198	0.73	0.27	-	-	-
3	148,100	0.65	0.26	0.08	-	-
4	73,636	0.59	0.27	0.10	0.04	-
5	33,496	0.53	0.28	0.12	0.05	0.02

Notes: This table shows the percentage of teams of various sizes collaborating across one or more EINs. For instance, the table reports that in 27% of two-inventor teams, the inventors are in two EINs, and that in 5% of five-inventor teams, the inventors are scattered across five EINs. Therefore, collabroations across EINs are quite frequent.