Experimenting strategically:
inter-firm relationships and "in-the-field" innovation

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Abstract: Research suggests inter-firm relationships affect firm behavior and performance in various ways. Yet, we know little about how such relationships shape patterns of "in-the-field" experimentation, that is, costly, trial-and-error problem solving processes that precede innovation. In this paper, we argue that supplier firms experiment with buyers strategically. Drawing from prior work on buyer-supplier relationships, relationship asymmetry, and knowledge leakage, we hypothesize that supplier firms experiment with buyers with whom expectations for experimental learning are high and the risk of leakage of experimental learning is low. We test and find support our hypotheses in the US hydraulic fracturing industry, where service firms supply hydraulic fracturing services for oil producing firms. Our results have implications for our understanding of inter-firm relationships and how they interact with processes of innovation.

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Introduction

Firms experiment, that is, engage in "trial and error problem-solving processes" as a necessary precursor to innovation (Thomke et al. 1998, Thomke and Kuemmerle 2002). Often this involves "in-the-field" experimentation, i.e., trialing prototype products, services, or inputs to processes to learn how they in the real world and thus refine, develop, or drop them. For supplier firms linked to buyer firms via value chain relationships this involves experimenting *within* inter-organizational exchange relationships. For instance, in our empirical context, oil field service firms occasionally experiment with new inputs to the hydraulic fracturing process whilst fracturing wells for oil producers (their buyers). An important strategic choice for such firms is therefore with who (specifically, with which buyer firms) to experiment. In this paper, we study how inter-firm relationships affect "in-the-field" experimentation, focusing in particular on the features of relationships that encourage or inhibit experimentation. We ask: which exchange partners are supplier firms more likely to experiment with?

Prior research suggests inter-firm relationships affect strategic choices and outcomes, including firm boundaries (Chatterji et al. 2019), employee engagement (Blader et al. 2015), and related firm performance (Dyer and Hatch 2006, Gibbons and Henderson 2012, Helper and Henderson 2014), among others. Prior literature also suggests that relationships contribute to mechanisms that likely underpin firm experimentation activities and strategic partnering choices relating to innovation. Relationships—developed via repeated exchange—enable the creation of relational capital, including shared norms, routines, and trust (Dyer and Hatch 2006, Zaheer and Venkatraman 1995) which enable firms to efficiently allocate resources and effort to maximize value creation (Elfenbein and Zenger 2017). By increasing the value of working with repeated partners, relational capital also encourages exchange continuity (and expectations thereof) (Baker et al. 2002, Dyer and Singh 1998, Elfenbein and

Zenger 2013, 2017, Madhok and Tallman 1998, Poppo and Zenger 1998). Collectively, these features of relationships facilitate the knowledge generation and transfer processes which underpin effective experimentation with new products and processes (i.e., experimental learning). However, relationships may also breed opportunistic behavior (Holloway and Parmigiani 2016, Noordhoff et al. 2011, Villena et al. 2011). Further, while relational capital stemming from long-term exchange relationships has the potential to create joint value (via various mechanisms including capability and information), the appropriation of value will often be asymmetric (Bidwell and Fernandez-Mateo 2010, Elfenbein and Zenger 2017, Holloway and Parmigiani 2016, Sorenson and Waguespack 2006), and the expectation of asymmetries will influence partnering choices (Elfenbein and Zenger 2017).

Supplier-firm-led experimentation has important potential benefits for supplier firm performance, by enabling supplier firms to expand and improve their future service offerings. "In-the-field" supplier-led experimentation can uncover what works (and what doesn't) in a real world setting. However, experimentation has costs. Experimenting instead of following the established standard typically negatively affects short-run performance (as we find in our setting) since most experiments fail. Simply put, supplier firms can learn by experimenting with new solutions but experimental learning will be costly. Thus, in choosing who to experiment with, we argue supplier firms will choose buyers with whom experimental learning is most likely, i.e. buyers with whom they have a prior relationship. Experimenting with buyers also risks knowledge leakage (Arora and Merges 2004, Pahnke et al. 2014). Thus, we hypothesize that suppliers will experiment buyers with whom the suppliers can dictate the flow and direction of knowledge leaks, and hence capture the full learning benefits of experimentation.

Our empirical context is the U.S. crude shale oil industry from 2013 to 2018. In this industry, suppliers (hydraulic fracturing service firms) prepare wells for oil production, i.e., “complete” wells, while buyers (oil producers) own the property rights over the subsequently extracted oil. We use well-level data from Rystad Energy for 24,669 U.S.-located wells completed between 2013 and 2018 for 377 buyer firms by 45 supplier firms. As shale oil extraction is a relatively young industry, supplier firms actively experiment in the inputs and processes involved in well completion to uncover and refine new inputs and input combinations that either increase production or decrease costs or both (Curtis 2016, 2017). Using well-level data on completion services provided by hydraulic fracturing service firms to oil companies allows us to identify experimentation within inter-firm relationships accounting for differences across time, location, and supplier firms and buyer firms. For example, we observe the 103 wells completed by Halliburton (supplier) for EOG (buyer) in this period, as well as all wells completed by Halliburton for other oil producers and all other EOG wells completed by other supplier firms. Seeing within- and across- relationship activity allows us to focus on relationship-level factors. To study experimentation, we use one crucial input in hydraulic fracturing: proppant. Fracturing a well involves, first, injecting fracturing fluid into shale rock using sufficiently highly pressurize to break the rock down, followed by a proppant slurry Proppant is a solid, sand-like material that keeps the (very) small fractures in the well open thus enables oil to flow. For each well, we observe whether an “experimental” proppant was used, which we define as a rare chemical combination.

We theorize that suppliers will experiment with partners with whom they have an established relationship, and further, within relationships where they can control knowledge leaks and thus expect to create and capture maximum value. Since much of the value from experimentation to the supplier comes from learning, we test this second aspect by looking at the opportunity for knowledge leakage outside the relationship stemming from leaks by either the supplier or the buyer. In terms of measurement, we flag a pair as an established relationship if the particular buyer-supplier pair worked together in 2013, our first year of observation. We measure the risk of buyer-led knowledge leakage as buyer importance for the supplier, or the share of supplier *j*'s wells completed for buyer *i*. Similarly, we measure the opportunity for supplier-led knowledge leakage as supplier importance for the buyer, or the share buyer *i*'s wells completed by supplier *j*.

Supporting our hypotheses, we find that that experimentation is more likely when the supplier and buyer have an established exchange relationship. In concrete terms, a history of prior exchange is associated with 10-12 percentage point (or ~50%) increase in the likelihood of experimentation. Among those with a history of prior exchange, experimentation is more likely when the supplier controls knowledge leakage and thus is more likely to benefit from experimentation. Specifically, experimentation is more likely when the supplier is more important for the buyer (and hence the buyer has fewer outside suppliers to leak information to) and when the buyer is less important for the supplier (and hence the supplier has many outside partners to benefit from their experimental learning. Our main specifications include buyer, supplier, play, and year fixed effects; we also run analysis including buyer-play, supplier-play, play-year, buyer-year and supplier-year fixed effects to investigate the role of time- and location-varying partner characteristics that may be driving experimentation within relationships.

Underpinning our logic and main analysis are several key assumptions. First, we presume that we are capturing purposeful experimentation not unsupervised accidents or mistakes. To explore this, we examine whether successful experimental proppant combinations are replicated over time, i.e. adopted in the process of completing future wells. We find successful experimental formulations are indeed increasingly more likely to be used in future years. Concretely, an experimental proppant combination from 2013 that was successful (i.e., had above-median production among wells completed in 2013) has 1% higher chance of replication (being used in another well) in 2015 (two years after successful experimentation), 2% higher chance in 2016, 3% and 4% higher chance in 2017 and 2018 (five years after successful experimentation), compared to all other proppant combinations. We also find failed experimental combinations are much less likely to be used compared to successful experimental proppants. These results support our argument that we are documenting purposeful experiments and not unsupervised accidents.

Second, we implicitly presume experimentation is costly, i.e. on average, associated with decreased production vis-à-vis non-experimental inputs, in terms of estimated ultimate recovery of oil, and hence the value from experimenting is primarily in experimental learning (including learning what doesn't work). Correspondingly, we find that a well completed using an experimental proppant is on average 10% less productive than an otherwise similar well using more typical proppant. Third, we also presume that experimentation is supplier-driven; we provide some contextual details to support this assumption.

This paper contributes to both inter-firm relationship and experimentation/innovation literatures. First, we contribute to the relationship literature by introducing experimentation, an important precursor of innovation, as a focal outcome. Experimentation is unique in that the value created is largely in the knowledge generated, i.e., learning what works, when, with what, and where, rather than in the current period transaction. Thus, relationship features that shape both knowledge creation and the potential for knowledge leakage dictate patterns of "in-the-field" experimentation. Second, contributing to the innovation literature, we empirically document pre-innovation stages of experimentation, often lacking in the literature due to inability to capture experimentation (trial-and-error activity) in large samples. Much of the innovation literature uses patent data, and therefore captures successful outputs of experimentation. However, our results suggest that successful experiments (i.e., those that perform above the median) are quite rare even among the most advanced firms. Our results also suggest a firm's ability to benefit from experimenting depends on controlling how the experimentation-based knowledge “leaks” to competitors outside of the relationship via partner firms. Last, combining the two literatures, we generate new theory and provide evidence that the choice of who to experiment with (which partner firm) is a strategic choice. Collectively, by looking at patterns of experimentation within value chain relationships, this paper sheds new light on our understanding of the full process of process innovation.

Theory [*NOTE: This section is preliminary and incomplete*]

Experimentation is a costly trial-and-error process targeted at resolving uncertainty around new technologies and new contexts (Thomke et al. 1998, Thomke and Kuemmerle 2002). Alongside simulations and laboratory-type experiments, firms run “in-the-field” experiments to elucidate accurate measure of real world performance of new solutions. A core benefit from experimentation is learning and developing specific know-how of how the experimental inputs perform with other inputs, within various different processes, and within and across heterogeneous environmental conditions.

Supplier firms—those that sell products and services to buyers—experiment *with* their buyers when performing “in-the-field” experiments. The goal of experimenting—i.e. the expected benefits—lie in discovering and refining new, experimental solutions. Yet, experimentation is costly for both parties, since it typically involves decreased performance relative to the status quo. Collectively, the net benefits from experimentation activity within buyer-supplier partnerships will be driven by up by factors that increase the potential for effective trialing and evaluation, thus maximizing joint value derived from experimental learning. Firms will want to experiment with partners with whom they have established routines, communication patterns, and trust to enable the ongoing knowledge transfer and expectations of collaborative effort necessary for experimentation to generate said learning (Elfenbein and Zenger 2013, Jain 2013, Kellogg 2011). In other words, we expect that relational capital (i.e. prior partnering experience) will increase the likelihood of experimentation activity.

H1: An established relationship between buyer and a supplier increases the likelihood of supplier-led experimentation.

However, in deciding on experimentation partners, supplier firms aren't simply concerned with maximizing the learning value created via the experiment. Instead, firms also select experimentation partners based on the private value they expect to be able to get from engaging in experimentation with that particular partner. Prior literature has highlighted that relationship asymmetries drive who benefits (most) from the relational capital accrued from prior exchange (Bidwell and Fernandez-Mateo 2010, Sorenson and Waguespack 2006) and, further, that firms incorporate value capture considerations into their ongoing partnering choices (Elfenbein and Zenger 2017). This literature suggest that in general a key determinant of the private value will be the reliance on or importance of one partner for the other.

Because a main part of the value created via experimenting is in learning tacit information about how inputs work best "in-the-field", and, since learning is enabled by partner firms sharing in knowledge creation and transfer, a concern in choosing which firms to experiment with is protecting that information from leaking out. Existing literature on firm boundaries and suggests that this threat of knowledge leakage is a core aspect of choosing whether to internalize and how to manage innovation-related partnerships (Arora and Merges 2004, McCutcheon and Stuart 2000, Pahnke et al. 2014).

Simply put, the more a supplier on a particular buyer (in other works, the more important a buyer is for that supplier), the more the supplier would expect the buyer be able to capture the value from experimenting. In part, this is because the supplier is limited in the set of other buyers to whom it can "leak" the outcome of its experimental learning (i.e.

improved processes). As a result, suppliers will experiment less with buyers on which they are more reliant.

H2: In established relationships, the more important a buyer is for a supplier, the lower the likelihood of supplier-led experimentation

Conversely, suppliers worried about leakage to the competitors via buyer firms want to experiment with buyer firms that are highly reliant on them, i.e. where buyer leakage is less likely and less costly for the supplier.

H3: In established relationships, the more important a supplier is for a buyer, the higher the likelihood of supplier-led experimentation

Data

To test these hypotheses, we use data from the U.S. shale oil industry. To build our sample, we use data from Rystad Energy, a Norwegian oil and gas market intelligence firm who collects and compiles global oil industry information from both governmental and company sources. We use data for 24,669 U.S.-located oil wells completed during 2013-2018 by 45 oilfield service suppliers for 377 oil producers.[1] In hydraulic fracturing, oil producers (i.e. “buyers”) hire oil service firms (i.e., “suppliers”) to provide a variety of components and services for well drilling, fracturing, and other well pre-production processes. These processes may involve experimentation and in turn influence innovation outcomes (Ma and Holditch 2015). Our oil well level data allow us to study experimentation within relationships on a well-by-well basis. We also measure and model a particular well’s estimated productivity (in number of barrels of oil).

Dependent variable: We measure “experimentation” using a binary variable indicating whether a particular well was among the 25% rarest proppant combinations used

[1] Our main analytical sample is for 21,260 wells completed from 2014 to 2018. We use the 2013 year to document established relationships.

that year[2]. Proppant is a key input in the fracturing process as it props the horizontally-located fractures open (to varying levels of success) and thus enables the flow of oil from the well (Curtis 2017). In our sample, we observe 250+ proppant combinations (i.e., lists of proppant chemical ingredients). The most common, crystalline silica (quartz), is used in approximately 60% of our sample of well completions.

Key independent variables: We measure the age of the relationship using an indicator variable of whether an exchange relationship existed (a positive number of wells was completed together) in 2013, our first year of observation.[3] Our main analysis uses data from 2014 forward. We measure *buyer importance* for the supplier, as the share of supplier *j*'s wells completed for buyer *i*. We measure *supplier importance* for the buyer, as the share buyer *i*'s wells completed by supplier *j*.[4]

Control variables and robustness: We include buyer and supplier fixed effects in order to control for any stable buyer and supplier characteristics, such as their overall quality, which may also drive experimentation. We also control for the play in which the well is completed as different locations may require different inputs and thus more (or less) experimentation on average. A shale play is a particular deposit of shale viable for hydraulic fracturing, e.g., the Bakken Shale play in Western North Dakota and Eastern Montana. We also add year fixed effects to control for any time trends in experimentation (e.g. technological supply shocks).

In additional regressions we include alternative fixed effects that control for time and location variation in the capabilities or preferences of suppliers (or buyers) that might

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[2] Results are robust to measuring rareness within shale play (a shale deposit, e.g. Bakken Shale play) rather than across all wells. Results are also robust to using different cut-offs for rareness (e.g. 15%).

[3] We also tried other operationalizations for this construct, including longer time ranges (which limits the analysis sample accordingly). The results remain robust.

[4] For example, suppose a supplier *j* completes 20 wells for buyer *i* in 2014, and completes 100 wells in total whilst the buyer has 30 wells completed. Then the buyer importance (to supplier) would be 0.20 and supplier importance (to buyer) would be 0.67.

contribute to experimentation across partners if buyer-supplier pairs are localized in time or location. These include: supplier-year, buyer-year, play-year, supplier-play, and buyer-play fixed effects.

For ease of presentation and interpretation, we use linear probability models as the main specification (results using logit models are consistent). Our main specifications is:

$$experimental\_proppant_{k(ijlt)} = \beta_1 existing\_relationship_{ijt} + \beta_2 buyer\_importance_{ijt} + \beta_3 supplier\_importance_{ijt} + \beta_4 existing\_relationship_{ijt} \times buyer\_importance_{ijt} + \beta_4 existing\_relationship_{ijt} \times supplier\_importance_{ijt} + \gamma_{FE} + \varepsilon_{k(ijlt)}$$

The dependent variable *experimental_proppant* is indicates if an experimental proppant was used in the completion of a well k, for which i is the supplier, j is the buyer, l is the location (the play within which the well is located), t is the year when the well was completed, and ε_{ijlt} is the error term.

Results

First, we provide a brief overview of the descriptive statistics of our analytical sample. On average, each supplier completed on average 609 wells a year, while each buyer completed 123 wells: the average pairing completed 63 wells together. Each supplier worked with 45 buyers and each buyer worked with 3 suppliers on average in a given year. Further, approximately 70% of all wells were completed by pairs that have an established relationship (i.e., worked together in 2013).

Column 1 in Table 2 tests Hypothesis 1. We find a positive relationship between the having an established relationship and the likelihood of an experimental combination of proppant. A well completed by a buyer-supplier pair who worked together in 2013 is 10-12 percentage points (or more than 50%) more likely to have an experimental proppant. Thus, we find both statistically and economically significant support for Hypothesis 1.

To test Hypotheses 2 and 3, we explore how buyer importance (to the supplier) and supplier importance (to the buyer) and relate to well-level experimentation. Among wells completed within an established relationship, we find that buyer importance is associated with a decrease in the likelihood of experimentation, while supplier importance is associated with an increase in the likelihood of experimentation. These results are consistent with suppliers experimenting where they can control knowledge leaks. First, they maximize their own ability to "leak" knowledge to other buyers; and second, they minimize the buyer firm's ability to leak knowledge to other suppliers. Overall, the results suggest supplier firms experiment where the opportunity for experimental learning is high (i.e., in established relationships), where they can benefit the most in terms of leaking out their learnings across buyers, and where the risk of that experimental learning leaking out to other suppliers is low.

We run further analyses to examine the support for the logic underpinning our theoretical arguments laid out above. First, if suppliers are experimenting in order to uncover successful unique combinations of proppant, we should see that they are likely to replicate successful combinations once discovered. Hence, we would expect experimental combinations from year t to be increasingly more likely to be adopted, i.e. replicated, in the years $t+1$, $t+2$, $t+3$ and so on. Finding such a pattern would provide supporting evidence to our contention that these experimental combinations are indeed efforts of experimentation with an end goal of innovation: when they prove successful, they are likely to be increasingly and widely adopted. To investigate this, we flag all combinations of inputs (proppant) in the hydraulic fracturing process that were unique and successful in 2013. As before, we measure unique as rare proppants. We operationalize "successful" as a well that eventually produced above median amount of oil (Estimated Ultimate Recovery)[5] among all wells completed that year. We then check the subsequent incidence of the 2013 experiments over the following years. Our analysis in Table 3 predicts the likelihood a well uses one of the 2013 experimental proppants in the years 2014 and forward. We see that the coefficients associated with the each following year become statistically significant from 2015 onwards (approximately two years after the initial experimentation) onwards and grow larger over time. Thus, an experimental proppant combination from 2013 that turned out to be successful makes up 1% of combinations in 2015, 2% in 2016, 3% in 2017, and 4% in 2018 (Column 1). We also compare successful experiments to failed experiments (Column 2), and find that failed experiments almost entirely disappear from use (after 2 years). These results are consistent with the idea that our measure captures purposeful experimentation: a successful experiment from 2013 becomes more widespread over time, and failed experiments disappear.

Second, we wanted to investigate whether or not experimentation is costly. To do so, we test whether experiments are associated with a decline in performance for a given well. While we don't have direct measures of the cost of proppant, we test whether experimental proppants are associated with decreased productivity (and are thus costly for both suppliers and buyers). In Table 4, we see that wells with experimental proppant are associated with a sizeable decrease in total output (Estimated Ultimate Recovery): a well using such proppant produces ~28,000 barrels less in its lifetime, which represents around 10% of an average total well output in this sample. Thus, we find strong support for the idea that experiments are costly and therefore any expected benefits from experimentation are likely realized in the future (after the experiment) via experimental learning.

[5] Estimated Ultimate Recovery (EUR) is the amount that is potentially recoverable from an oil well and is a widely used metric of well productivity in the industry.

One additional assumption we make is that experimentation is supplier-led. An alternative view on our theory is that these experiments are buyer-led (i.e. that buyer firms demand experimental proppants from suppliers). The results from Table 4 do not support this view: otherwise similar wells using experimental proppants perform worse than non-experimental wells, which suggests experimentation is costly for buyer firms as well. Further, while buyer-led (or demand driven) experimentation is plausible in general, our understanding of this industry is that the incentives to experiment with fracturing inputs are overwhelmingly on the supplier side. Oil service firms typically hold the intellectual property associated with proppants and other inputs [*note: quantitative evidence on patenting to come*]. Further, the service contracts tend to be fixed price, and the market for fracturing services fairly competitive.

Within our context, and since experimentation is costly to both parties, one reason that suppliers are able to experiment is because they provide bundled inputs and services in well completion, including choice of inputs and input mix (the appropriate mix between fracking liquids and proppant) for fracturing, operating the pumps, administering artificial lifts, and many other services. In addition to avoiding direct price competition (Balachander et al. 2009), bundling may also facilitate experimentation by providing suppliers the opportunity to pursue learning opportunities without close scrutiny. As supportive excerpt from an annual review from one leading service provider reads:

"Innovation around a single element in the E&P [Exploration and Production] development chain cannot maximize efficiency in isolation. The new approach requires a complete understanding of what each element contributes to the entire chain. Schlumberger believes that achieving this will require a profound change in the way the industry operates and interacts – changing the way we work and yet also changing the very nature of that work". *Schlumberger 2017 Annual Report*

In sum, we argue the experimentation decisions about proppant as an input in hydraulic fracturing are supplier-led.

One additional plausible alternative theory of experimentation could be that suppliers experiment to show off an arsenal of possibilities in the varieties of inputs and approaches they can provide. By extension, this signaling argument would imply that newer relationships would be more prone to experimentation. However, we find that suppliers experiment more with buyers with whom they have an established relationship: this is inconsistent with an experimentation-as-quality-signaling story.

Discussion

We find that suppliers are most likely to experiment within established experiments, and when they can control and direct knowledge leaks. We theorize that the value of experimentation—which a costly, trial-and-error, problem solving process—lies in the learning it creates. Experimentation in-and-of-itself is costly, but it offers experimenters the opportunity to learn. We also see evidence of learning taking place: successful experiments are increasingly likely to be replicated over time while failed experiments are abandoned.

Relationships have been argued to lead to more productive practices (e.g. Gibbons & Henderson, 2012) thus creating value. However, the rewards from working with an established partner are often not equally distributed (Bidwell and Fernandez-Mateo 2010, Elfenbein and Zenger 2017, Sorenson and Waguespack 2006). Thus, the effect of relationships and relational features on experimentation and thereby innovation (S. Thomke et al., 1998; S. H. Thomke, 1998) is not clear-cut ex ante. This paper aims to contribute to both the inter-firm relationship and innovation literatures, which have largely evolved separately. This paper constitutes an early effort to integrate the two, asking to what extent inter-firm relationships facilitate or hinder experimentation. We highlight the role of relationships in facilitation experimentation, a necessary precursor to innovation, highlighting how firms can manage the knowledge leakage hazards associated with experimentating with other firms.

In addition to our main contributions, we also provide a response to prior research calling for more diverse measures of the processes and outcomes of innovation beyond patent counts and forward citations (Arora et al. 2017). We hope that our paper contributes to a new focus on different measures of experimentation which facilitate increased understanding of it and other key precursors to innovation. However, since proppant recombinations are a new measure of experimentation, they are subject to further validation.

This paper does not claim to delineate universal patterns between inter-firm relationships and experimentation. The context we study has several boundary conditions that may not be present in other settings: well-completion involves process technologies with locational specific knowledge demands; and, the experimental process we explore is supplier-led and the learning is about technological suitability rather than customer preferences or other factors. Further, "in-the-field" experimentation is especially valuable in this context, as, for proppants. lab experiments often are removed from real outcomes and observed differences in performance between lab and the real world of 10x or more (Liang et al. 2016). However, these features, and the fact that the oil industry is one of large economic significance make the context one where understanding experimentation patterns is of interest.

Conclusion

This study contributes to research on inter-firm relationships and innovation. We shed light on the types of relationships that are most prone to experimentation, which we characterize as a costly activity that produces experimental learning and thus a necessary precursor to innovation. We find supplier firms are most likely to experiment in established relationships where they can control and direct knowledge leaks. Supporting our logic, experimental inputs are found to be costly to undertake. Further, we also observe successful experiments are replicated and failed experiments abandoned. We hope that future research will further explore strategic experimentation and the different effects of relationships on experimentation across other settings, including looking at how industry and firm structure shapes both the incentive to experiment "in-the-field" and the effect of relationships on experimentation strategies.

Table 1. Summary statistics

	Mean	St.dev	Median	10th %	90th%
N wells by buyer i in year t	123	131	83	10	285
N wells by supplier j in year t	609	500	413	84	1251
N wells buyer-supplier ij in year t	63	91	34	4	143
N wells in play b in year t	976	595	987	159	1890
N buyers for supplier j in year t	45	33	32	6	96
N suppliers for buyer i in year t	3	3	3	1	7
Relationship since 1st yr of obs (2013)	70%				
Example of experimental proppant (2013)	Crystalline silica, quartz; Aluminum oxide; Iron oxide; Titanium oxide				

Table 2. Buyer-Supplier relationships and experimentation

	(1)	(2)	(3)
		Experimental proppant	
Old relationship (since 2013)	0.11810***	0.12538***	0.13113***
	(0.00877)	(0.00890)	(0.01367)
Buyer importance (to supplier)		-0.03922	0.01691
		(0.02571)	(0.02947)
Supplier importance (to buyer)		-0.04727***	-0.07350***
		(0.01321)	(0.01582)
Old X Buyer importance			-0.14483***
			(0.04062)
Old X Supplier importance			0.06586***
			(0.02330)
Observations	21,260	21,260	21,260
R-squared	0.35	0.35	0.35
Buyer FE	Yes	Yes	Yes
Supplier FE	Yes	Yes	Yes
Play FE	Yes	Yes	Yes
Year	Yes	Yes	Yes

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 3. Replication of successful experimental combinations over time

	(1)	(2)
	Successful experimental combination from 2013	
	All proppants	Experimental proppants
2014 completion year	0.00204	-0.03385
	(0.00330)	(0.03728)
2015 completion year	0.00917**	-0.05083
	(0.00384)	(0.05219)
2016 completion year	0.02210***	0.36334***
	(0.00467)	(0.09432)
2017 completion year	0.03232***	0.18413**
	(0.00423)	(0.07397)
2018 completion year	0.04418***	0.16624**
	(0.00483)	(0.07872)
Observations	24,669	430
R-squared (pseudo)	0.20	0.80
Buyer FE	Yes	Yes
Supplier FE	Yes	Yes
Play FE	Yes	Yes

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 4. Experimental input and well performance

	(1) Total output from a well (estimated ultimate recovery)
Experimental proppant	-21,798.102***
	(4,202.904)
Observations	21,217
R-squared	0.369
Buyer FE	Yes
Supplier FE	Yes
Play FE	Yes
Year FE	Yes

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

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