Straw-Into-Gold Innovation*

Martin Beraja UC Berkeley

Noam Yuchtman LSE

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1 Introduction

Economists have so far understood long-run growth as coming from the accumulation of reproducible factors (Lucas Jr, 1988; Rebelo, 1991), and from technological innovations that augment non-reproducible factors (Romer, 1994; Parente and Prescott, 2002; Aghion et al., 2014) or create new input varieties from known available resources (Romer, 1990). Yet, many important innovations are different in nature. They create new inputs from resources that were previously overlooked, unknown to be valuable — they *turn straw into gold*.

Consider OpenAI's use of online content in training ChatGPT or Google's and Facebook's use of consumer data in digital advertising. Online content, if not copied, was freely available under fair use; consumer data (e.g., search queries, browsing histories) was seen as "data exhaust" (Zuboff, 2019). The nature of each innovation was to recognize the value of online content and consumer data, and turn them into productive inputs. History offers many other important examples, including the discovery of airwaves as a vehicle for radio and TV broadcasting, the transformation of oil refinery waste into plastics, the use of sand in the production of ceramics, and in ancient times, the conversion of wild animals into domesticated sources of motive power.

Such technological innovations occured in a very different institutional context than the traditional innovations studied in the literature. Property rights over previously un-

*Martin Beraja: maberaja@berkeley.edu. Noam Yuchtman: n.yuchtman@lse.ac.uk. We are grateful to Juan Manuel Escolar for excellent research assistance.We thank Dave Donaldson, Ernesto Dal Bo, Avi Goldfarb, Dimitris Papanikolaou, Esteban Rossi-Hansberg, Tom Sargent, Steve Tadelis, Jean Tirole, andIvan Werning for helpful discussions.

recognized resources are inevitably poorly defined prior to the innovation that turns them into productive inputs.[1] As a result, innovators are confronted with the choice of appropriating the overlooked resource, risking conflict with counterparties who may have competing claims, or contracting with these counterparties beforehand. In practice, conflicts over property rights have often arisen and have been resolved through litigation and regulation, as seen in disputes over the ownership and fair use of online data and the allocation of radio and TV spectrum.

In this paper, we identify and analyze a new class of *straw-into-gold* innovations, which the literature has not yet conceptualized. To document and define this class, we develop several historical case studies and introduce a taxonomy organized around the nature of the underlying resource. Then, we present evidence from U.S. law reviews to illustrate how appropriation patterns have evolved over time. Lastly, we present a model of straw-into-gold innovation that captures the defining features of the class: (i) the creation of productive inputs out of previously unrecognized resources and (ii) the lack of well established property rights ex-ante. We show that economic rents from appropriation of unrecognized resources can sustain innovation, beyond traditional monopoly rents from producing new input varieties out of known resources (Romer, 1994). Moreover, property rights emerge as a consequence of innovation, not as pre-condition for it (North, 1981; Hornbeck, 2010). The institutions through which property rights are established — not merely protected — thus become crucial determinants of innovation and economic growth.

Our analysis most directly contributes to the literature on growth arising from ideas and innovations (Romer, 1990; Aghion and Howitt, 1992; Mokyr, 1992). We highlight an economically important class of innovations that has not received focused attention from economists up to now: straw-into-gold innovations which create novel inputs from unrecognized resources. We describe how and why the economics of this class of innovations differs from the innovations usually studied: the inherent absence of well-defined property rights over the new factor fundamentally changes the innovator's problem due to information revelation when contracting and the chance of extraordinary rents when resolving conflicts. Our analysis reveals a source of potential rents – arising from conflict over ill-defined property rights – that incentivize innovation, complementing Schumpeterian monopoly rents (as inSchumpeter, 2013; Aghion and Howitt, 1992).

Our finding that the absence of property rights over a new factor can induce innovation is also related to the literature on intellectual property rights. A substantial literature

[1] In contrast, known resources are typically exchanged in markets with well established property rights.

argues that strong intellectual property rights, in the form of patents, may be unnecessary – or even deleterious – for innovation. Moser (2013; 2016) reviews historical evidence of innovation in the absence of patent protection. Anton and Yao (2004) and Hall et al. (2014) present trade-offs between patenting and protecting intellectual property informally. Boldrin and Levine (2002; 2008a; 2008b), Bessen and Maskin (2009), and Henry and Ponce (2011) all argue that patents are not necessary for innovation, and that innovation may even be enhanced by weaker intellectual property protection. These papers, however, focus on property rights over the output of a technology or the copying of ideas. In contrast, we focus on contested property rights over resources that are made valuable by the discovery of a technology. Closest to our work are the analyses of Williams (2013) and Murray et al. (2016). They document the adverse consequences of intellectual property rights protection of biomedical research that is used as an input into downstream innovation. Our analysis differs from theirs in that: (i) we do not take property rights as given – they are to be determined in our context either through contracting or conflict; and, (ii) in our context, the innovator may prefer to leave property rights ill-defined.

Finally, in studying the endogenous determination of property rights, our analysis contributes to the literature arising from Coase (1960). Much of this work highlights the cost of insecure property rights for productivity and economic growth (North, 1981; Engerman and Sokoloff, 2005; Acemoglu and Johnson, 2005; Hornbeck, 2010). In contrast, we highlight a dimension of ill-defined property rights that can incentivize innovation and thus growth: weak property rights provide an opportunity for innovators to extract rents. That these rents induce conflict, rather than ex ante contracting, is difficult to avoid given the nature of information revelation when contracting and the necessity of writing incomplete contracts (Tirole, 1999 and 2009; Bolton and Faure-Grimaud, 2010). It suggests a contentious political economy of innovation in which entrepreneurs aim to shape the legal and regulatory environment in their favor, through litigation and lobbying.

2 The Class of Straw-into-Gold Innovations

This section documents and defines the class of straw-into-gold innovations. We begin with detailed historical case studies—generative artificial intelligence, digital advertising, and radio and television broadcasting—that illustrate a common mechanism: innovation turns a previously overlooked or weakly valued resource into a productive input before property rights over that resource are clearly defined. In each case, innovators face a choice between ex ante contracting and ex post appropriation, with conflict, litigation, and regulation emerging as property rights are subsequently established.

We then explore the boundaries of straw-into-gold innovation by examining cases that share some, but not all, of its defining features, such as unreachable resources, complementary inputs, abundant resources, and search-and-discovery activities. This discussion clarifies when the core economics emphasized in the paper applies, and when it does not, and distinguishes straw-into-gold innovation from process improvements and Romerian innovation based on known, well-defined inputs.

Next, we introduce a taxonomy that classifies straw-into-gold innovations according to the nature of the underlying resource—data, material natural resources, immaterial natural resources, waste, and spatial commons—highlighting that the phenomenon cuts across technologies and historical periods. To document its broader scope, the section draws on McNeil's Encyclopaedia of the History of Technology to show that straw-into-gold dynamics appear throughout the history of technological change.

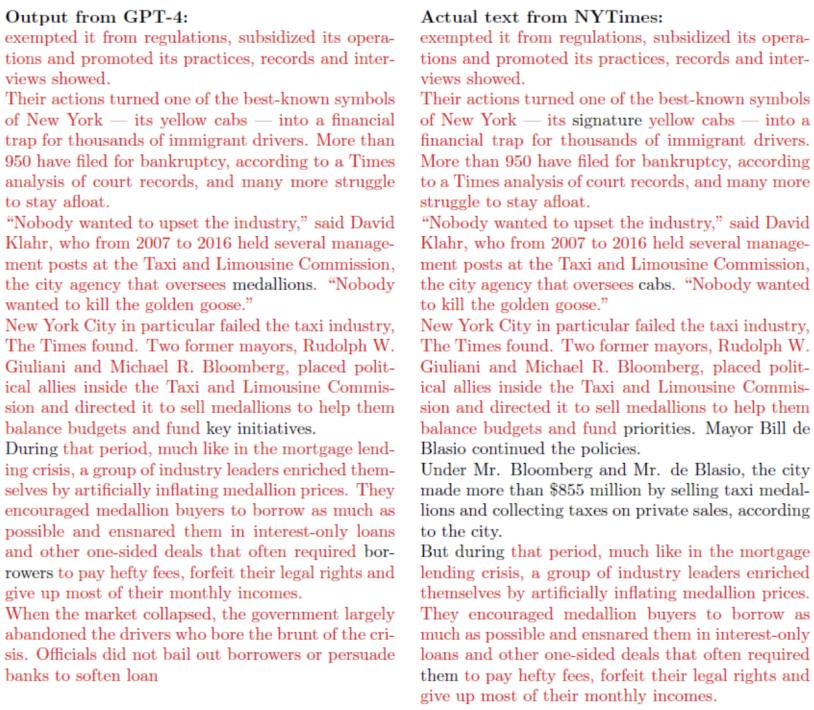
Finally, we present systematic evidence from U.S. law reviews, classifying articles according to whether they study appropriation conflicts over specific resources. This evidence reveals a historical shift in the frontier of appropriation—from material resources in the early twentieth century, to immaterial resources mid-century, and to digital resources in recent decades—underscoring the paper's central theme: straw-into-gold innovation arises when technological change outpaces the institutional definition of property rights, motivating the formal model that follows.

2.1 Case Studies

2.1.1 Generative artificial intelligence

The origins of artificial intelligence (AI) trace back to the 1956 Dartmouth Summer Research Project, marking the field's official birth. For decades, progress was stifled by limited computing power and scarce data to train AI algorithms. But since the early 2000s, the field has rapidly advanced, driven by breakthroughs in computing and the explosion of big data online. This progress has recently culminated in the emergence of generative AI technologies like ChatGPT or Stable Diffusion, heralding a transformative era in the industry.

ChatGPT is an advanced language model that can generate human-like text based on the input it receives. It was trained on vast amounts of text from books, websites, and other written sources, enabling it to produce responses to a variety of user prompts. The New York Times (NYT) has recently taken legal action against OpenAI — the company behind ChatGPT — alleging unauthorized use of its articles in training the AI model. The core of the complaint is that OpenAI knowingly scraped NYT articles without ob-



Output from GPT-4:
exempted it from regulations, subsidized its operations and promoted its practices, records and interviews showed.
Their actions turned one of the best-known symbols of New York — its yellow cabs — into a financial trap for thousands of immigrant drivers. More than 950 have filed for bankruptcy, according to a Times analysis of court records, and many more struggle to stay afloat.
"Nobody wanted to upset the industry," said David Klahr, who from 2007 to 2016 held several management posts at the Taxi and Limousine Commission, the city agency that oversees medallions. "Nobody wanted to kill the golden goose."
New York City in particular failed the taxi industry, The Times found. Two former mayors, Rudolph W. Giuliani and Michael R. Bloomberg, placed political allies inside the Taxi and Limousine Commission and directed it to sell medallions to help them balance budgets and fund key initiatives.
During that period, much like in the mortgage lending crisis, a group of industry leaders enriched themselves by artificially inflating medallion prices. They encouraged medallion buyers to borrow as much as possible and ensnared them in interest-only loans and other one-sided deals that often required borrowers to pay hefty fees, forfeit their legal rights and give up most of their monthly incomes.
When the market collapsed, the government largely abandoned the drivers who bore the brunt of the crisis. Officials did not bail out borrowers or persuade banks to soften loan

Actual text from NYTimes:
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Under Mr. Bloomberg and Mr. de Blasio, the city made more than $855 million by selling taxi medallions and collecting taxes on private sales, according to the city.
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Figure 1: Exhibit from *The New York Times Company v. OpenAI, Inc., et. al. District Court of Southern New York, 2023*.

taining a license, violating copyright law. The lawsuit claims that, when users prompt ChatGPT, the AI could generate outputs that closely mimic NYT articles — sometimes outright inventing them — or produce exact copies — what is known as "regurgitation" — thus misleading users and infringing on the newspaper's intellectual property rights. For example, the lawsuit presents Figure 1 as an exhibit and states that:

> "165. On information and belief, Defendants' infringing conduct alleged herein was and continues to be willful and carried out with full knowledge of The Times's rights in the copyrighted works. As a direct result of their conduct, Defendants have wrongfully profited from copyrighted works that they do not own."
>
> The New York Times Company v. OpenAI, Inc., et. al. District Court of Southern New York, 2023.

OpenAI argues that the New York Times lawsuit lacks merit. For instance, OpenAI asserts that their use of publicly available internet data, including from news sources, is protected by the "fair use" doctrine. This doctrine allows limited use of copyrighted material for purposes like research and education. Moreover, they address concerns about

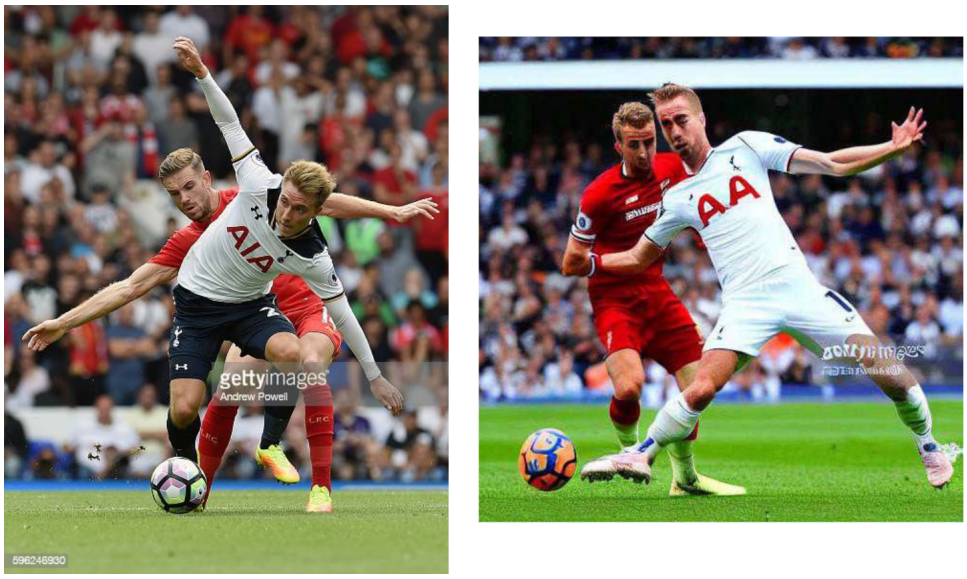


Figure 2: Exhibit from *Getty Images Inc. v. Stability AI, Inc. District Court of Delaware, 2023*.

"regurgitation" explaining that these occurrences are unintentional and rare, and that efforts are made to minimize them.[2]

Similarly, Getty Images has filed a lawsuit against Stability AI, the company behind the tool Stable Diffusion. The tool is designed to generate high-quality images from user text prompts, making it a popular choice for AI-generated art. It was trained on a massive dataset of images and text descriptions, sourced from publicly available online platforms such as image hosting websites, art communities, and social media. Getty alleges that Stability AI unlawfully scraped a vast number of their images, resulting in the unauthorized reproduction and potential modification of copyrighted material. The lawsuit also claims that Stability AI's actions were conducted with knowledge of the infringement. For example, the lawsuit presents Figure 2 as proof and states that:

> "58. Upon information and belief, Stability AI has knowingly removed Getty Images' watermarks from some images in the course of its copying as part of its infringing scheme. At the same time, however, as discussed above, the Stable Diffusion model frequently generates output bearing a modified version of the Getty Images watermark, even when that output is not bona fide Getty Images' content and is well below Getty Images' quality standards."
>
> Getty Images Inc. v. Stability AI, Inc. District Court of Delaware, 2023.

To conclude, generative artificial intelligence has elevated text and image data to a fiercely contested asset, essential to the success of AI technologies. The boundaries around

[2] See https://openai.com/index/openai-and-journalism/ for these and other counterarguments.

data ownership and its use in training AI models have been loosely defined before the advent of tools like ChatGPT and Stable Diffusion, sparking major legal disputes. By all accounts, the companies behind these tools took a calculated gamble, banking on the expectation that courts and regulatory bodies would endorse their extensive data usage practices without explicit permissions. The evolution of the AI industry might change significantly if the legal framework were to enforce stringent protections for intellectual property going forward.

2.1.2 Digital advertising

The late 1990s and early 2000s saw the rise of the commercial internet and, with it, new ways to connect businesses to consumers. Search engines and social networks initially provided free services to users, but soon faced the question of monetization. Beyond their breakthrough technical products — Google's search algorithm and Facebook's social media platform — both companies pioneered digital advertising models that transformed consumer data into a new factor of production.

At first, personal data such as search queries, clicks, browsing histories, and social interactions were considered a byproduct of digital activity, holding little obvious economic value. Google's innovation turned these traces into a new factor when it introduced AdWords (2000) and later AdSense, which matched advertisements to users based on their queries and online behavior. This mechanism relied on storing and analyzing enormous amounts of user data, allowing advertisers to target audiences with unprecedented precision. Facebook followed a parallel path: its platform initially thrived by connecting friends and communities, but a key breakthrough came when it leveraged its massive trove of demographic and social data to sell highly targeted advertising. In both cases, the technological product itself was essential, but the value creation derived largely from converting user data into an input for advertising markets. What had been "digital exhaust" became the fuel for an advertising ecosystem worth hundreds of billions of dollars.

The extraordinary rents from digital adverstising hinged on the absence of clearly defined property rights over personal data. Users generated the data, platforms stored and processed it, and advertisers reaped the benefits of more efficient targeting. Conflicts soon arose as individuals, regulators, and rival firms contested ownership and control. One of the most visible came with the Cambridge Analytica scandal (2018), when data from tens of millions of Facebook users was harvested through a third-party app and used for political targeting. In congressional testimony, Facebook CEO Mark Zuckerberg conceded:

> "We didn't take a broad enough view of our responsibility, and that was a big mistake. It was my mistake, and I'm sorry. I started Facebook, I run it, and I'm responsible for what happens here."
>
> United States Senate, Joint Hearing of the Commerce and Judiciary Committees, April 10, 2018.

The scandal underscored how platforms had treated personal data as a freely appropriable factor, even when users themselves had not consented to its secondary use.

Regulators, particularly in Europe, moved to assert individual rights. The General Data Protection Regulation (GDPR, 2018) established strict limits on data collection and processing. Article 5 of the Regulation mandated that personal data must be "collected for specified, explicit and legitimate purposes and not further processed in a manner that is incompatible with those purposes," while Article 17 introduced a new "right to erasure," or "right to be forgotten." These provisions directly challenged the business models of Google and Facebook, which had thrived on the assumption that data once collected could be repurposed indefinitely.

In the United States, regulators pursued antitrust claims. In its 2020 complaint against Facebook, the Federal Trade Commission alleged:

> "By using its control of user data and its market dominance, Facebook has suppressed, neutralized, and deterred the emergence of competing social networking providers, depriving users of the benefits of competition and depriving advertisers of an independent alternative."
>
> FTC v. Facebook, Inc., U.S. District Court for the District of Columbia, 2020.

These disputes illustrate how consumer data, once treated as exhaust, became a fiercely contested asset.

Looking back, both Google and Facebook took a gamble. They appropriated consumer data without explicit contracts or licenses, betting that courts and regulators would tolerate — or even legitimize — their practices after the fact. The wager succeeded: digital advertising grew into a multi-hundred-billion-dollar industry, and Google and Facebook captured extraordinary rents. The trajectory of the digital industry might have been very different had legislators and courts defined ownership of personal data more strictly in its early years.

2.1.3 Radio and TV broadcasting

When radio emerged in the early 20th century, the core innovation lay not only in the technical development of transmitters and receivers, but also in the recognition that the electromagnetic spectrum itself could serve as a factor of production. Airwaves, once considered a scientific curiosity with little economic significance, became the indispensable medium through which music, news, and entertainment could be transmitted to mass audiences.

The early years of broadcasting were marked by disorder. By the early 1920s, thousands of amateur and commercial stations transmitted without coordination, often using the same frequencies. Signals collided, programs overlapped, and listeners were left with static and confusion. As one journalist observed at the time, "etheric bedlam reigned" in American cities. The problem was not technological, but institutional: property rights over the airwaves were undefined. Broadcasters appropriated frequencies simply by using them, and disputes quickly followed.

The federal government responded with the Radio Act of 1927, creating the Federal Radio Commission (FRC) and granting it authority to allocate frequencies "as public convenience, interest, or necessity requires." Courts reinforced this principle. In Whitehurst v. Grimes (1927), a Kentucky broadcaster challenged the Commission's decision to revoke his license, arguing that he had a property right to continue using his frequency. The court rejected the claim, holding that "no person is the owner of a radio frequency" and that the spectrum belonged to the public, managed by the government in trust.

Television raised the stakes further. Broadcast licenses in metropolitan areas became immensely valuable, conferring monopoly-like control over access to households. Legal disputes centered not only on interference, but also on content and network dominance. In NBC v. United States (1943), the Supreme Court upheld the FCC's authority to impose chain broadcasting regulations that limited the power of networks over local affiliates. The Court emphasized that broadcasters were "granted the free and exclusive use of a limited and valuable part of the public domain" and therefore subject to heightened regulation.

Yet the process of assigning licenses remained controversial. Through the mid-20th century, the FCC relied on comparative hearings and lotteries, methods often criticized as inefficient, politicized, and susceptible to lobbying. As the demand for spectrum expanded with the rise of mobile telephony, regulators sought a new approach. Beginning in 1994, the FCC introduced spectrum auctions, allowing frequencies to be allocated through competitive bidding rather than administrative discretion. These auctions, covering not only broadcast frequencies but also bands for cellular and later broadband ser-

vices, raised tens of billions of dollars for the U.S. Treasury and were widely adopted by other countries.

In retrospect, radio and television broadcasting turned the electromagnetic spectrum into a valuable and contested factor of production. The initial period of appropriation — when stations claimed frequencies by force of transmission — resembled the appropriation of online data by generative AI and digital advertising companies: a gamble on weakly defined property rights. Once the state asserted control, however, firms were forced to secure their rights through licensing and, eventually, through market-based auctions. The profitability of broadcasting and, later, of wireless communication hinged not only on technical advances but on how governments chose to define, regulate, and allocate ownership-like rights to the airwaves.

2.2 Exploring the Boundaries of Straw-into-Gold Innovation

Not all economically important innovations fit cleanly into the straw-into-gold category. To clarify what distinguishes this class, it is useful to examine a set of boundary cases that share some—but not all—of its defining features. These cases help delineate when the core economics we emphasize applies, and when it does not.

2.2.1 Unreachable Resources

In some cases, a resource was known to be valuable ex ante, but was believed to be technologically or economically unreachable. Innovation does not discover value, but rather makes access feasible. Because the resource is perceived as unreachable, agents have little incentive to invest in defining or enforcing property rights beforehand—especially when doing so is costly. As in classic incomplete contracting environments, no one bothers to contract over a resource that cannot yet be exploited.

When an innovation suddenly makes the resource reachable, the same forces emphasized in straw-into-gold innovations arise. Property rights are ill defined at the moment the resource becomes usable, and innovators face a choice between appropriation and ex ante contracting, with the latter revealing information and potentially unraveling rents. The difference from the canonical case is epistemic rather than economic: the resource's value was known, but its usability was not.

Historical examples include oil prior to modern drilling techniques, deep-sea minerals before offshore extraction technologies, and extraterrestrial resources such as asteroids. In each case, innovation converted a latent resource into an economically relevant

input, triggering conflict, legal disputes, and institutional responses once access became possible.

2.2.2 Complementary Inputs

In other cases, the innovation does not directly transform an overlooked resource into a new input. Instead, it requires the use of a complementary input that had previously been ignored, underutilized, or treated as a commons. If innovation is interpreted narrowly as the core technical breakthrough, the complementary input appears peripheral. But if innovation is understood more broadly—as the commercialization, scaling, and deployment of a technology—then the complementary input becomes central to value creation.

Under this broader interpretation, the complementary input is the "gold." Its prior neglect implies that property rights were weak or nonexistent, and its sudden importance creates scope for appropriation and conflict. The relevant innovation lies as much in recognizing how to mobilize this input as in the underlying technology itself.

Classic examples include overhead urban space used for electricity distribution, airspace around airports for commercial aviation, urban airspace for drones, and orbital slots for satellites. In each case, commercialization required access to a resource that was not initially priced, traded, or clearly owned. Some modern platform examples—such as ride-sharing or short-term rentals—can also be interpreted through this lens, as they rely on previously unused capacity whose ownership and permissible use were ambiguous.

2.2.3 Abundant or Non-Excludable Resources

A third boundary case arises when innovation does transform an overlooked or unknown resource into a productive input, but the resource is abundant or effectively non-excludable. In these environments, innovators may still appropriate the resource, but appropriation does not generate sustained conflict or rents. Property rights may remain weak without affecting incentives, because scarcity is absent.

In such cases, rents arise primarily from product innovation—protected, for instance, by patents or trade secrets—rather than from control over the resource itself. The core mechanism emphasized in this paper, whereby expected rents from appropriation sustain innovation, plays a limited role.

Examples include solar energy, animal domestication, and historical silk production in China. Silkworms were abundant, but the techniques for cultivation and silk extraction were protected. The innovation did not depend on excluding others from the resource,

but on protecting the idea.

2.2.4 Search and Discovery

Finally, there are cases in which the idea is not technological in nature at all. Instead of transforming an unknown resource into an input, innovators search for unknown sources of already valuable inputs. Here, the uncertainty concerns location or discovery rather than usability.

The economics shares similarities with straw-into-gold innovation—property rights are often ill defined prior to discovery, and rents arise from appropriation rather than contracting—but the mechanism is fundamentally different. The innovation is not about creating a new factor of production, but about locating one. As a result, we treat these cases as distinct from straw-into-gold innovations, even though they involve similar institutional frictions.

2.2.5 Scope and Relation to Other Forms of Innovation

The cases above clarify the boundaries of straw-into-gold innovation, but they also highlight its breadth. Straw-into-gold innovations are not confined to a narrow set of technologies or historical episodes. Rather, they span a wide range of domains and recur whenever innovation renders previously overlooked resources economically relevant under weak or nonexistent property rights.

At the same time, it is important to distinguish this class from other well-studied forms of innovation. First, some important innovations are primarily process improvements, such as the assembly line or the Bessemer process. These transform production efficiency without creating new inputs or revaluing resources. Second, many technologies create new input varieties out of existing, well-defined resources—what we refer to as Romerian innovation. Examples include steel from iron and coal, computers, early internet technologies, and operating systems. In these cases, resources are already traded in markets with established property rights, and innovation rents arise through monopoly power or intellectual property protection.

While Romerian innovation can generate speculative rents—particularly when innovators acquire inputs before others update beliefs about their value—these rents stem from informational asymmetries rather than from contested ownership. The innovator can rent or purchase the resource outright; conflict is not intrinsic to the innovation process.

Straw-into-gold innovation differs precisely because property rights over the relevant

resource are not well defined at the moment it becomes valuable. Innovation precedes ownership. As a result, the innovator's problem is not simply one of pricing or exclusion, but of choosing between appropriation and contracting under uncertainty and information revelation.

2.3 A Taxonomy of Straw-into-Gold Innovations

The table classifies straw-into-gold innovations according to the nature of the "straw" — that is, the type of resource that is transformed into a productive input — along five recurring categories: data, material natural resources, immaterial natural resources, waste, and spatial commons. This classification highlights that straw-into-gold innovation is not defined by a particular technology, but by the kind of resource whose economic value is revealed by innovation.

Table 1: A Taxonomy of Straw-into-Gold Innovations

Category of Straw	**Innovation**	**Straw (Ex-Ante)**	**Gold (Ex-Post)**	**Appropriatio**
Data	Generative AI (ChatGPT); Digital advertising (Google, Facebook); Ambient data (voices, images, behavioral traces)	Unpriced or weakly protected information; "data exhaust"	Productive input into prediction, targeting, and content generation	Yes (ofte contested)
Material Natural Resources	Boric acid; Sand into ceramics; Silicon for semiconductors; Silkworms	Known physical resources with limited or niche value	Essential industrial or intermediate inputs	Mixed
Immaterial Natural Resources	Radio spectrum; Geosynchronous orbit; Solar energy; Nuclear and quantum resources	Abstract natural endowments treated as commons	Scarce inputs into communication, energy, or computation	Context-dependent
Waste	Plastics; refinery by-products; digital waste reused for training	Residuals or by-products with zero or negative value	Valuable intermediate goods or inputs	Yes (initially low conflict)
Spatial Commons	Overhead space for electricity; Urban airspace for drones; Airport airspace for aviation	Public or unregulated space	Access-constrained infrastructure input	Yes (frequen conflict)

In data-based innovations, the straw consists of information that was previously treated as exhaust or as an ambient by-product of economic activity. Innovation lies in recognizing how such data can be aggregated and used productively, often before ownership or usage rights are clearly defined, giving rise to appropriation and conflict. In material natural resource innovations, the straw is a physical resource whose commercial value was unknown, niche, or technologically inaccessible. Innovation transforms these materials into essential inputs. Whether appropriation leads to conflict depends on scarcity and

on the feasibility of excluding others from access. In immaterial natural resource innovations, the straw is an abstract or non-physical endowment—such as spectrum, orbital positions, or solar exposure—that was initially treated as a commons. Innovation reveals that these resources are scarce or congestible, at which point control becomes valuable and disputes over access and ownership emerge. In waste-based innovations, the straw consists of residuals or by-products with little or negative value. Innovation converts waste into a productive input. Appropriation is typically uncontested at first, but conflict can arise as scale increases or alternative uses become salient. Finally, in spatial commons innovations, the straw is access to physical space that was previously unregulated or collectively used. Commercialization transforms space into an input whose value depends on exclusivity, frequently triggering conflict and regulatory intervention.

2.4 McNeil's Encyclopedia

To assess the scope of straw-into-gold innovation, we turn to McNeil's *An Encyclopaedia of the History of Technology* (1990). The book contains 21 chapters, organized into 5 broad areas of innovation. We write in parenthesis some examples of new resources associated with each. Appendix B describes each in a concise manner.

1. *Materials*: Non-ferrous metals (deep sea minerals); ferrous metals (aboriginal land in Australia); chemicals and allied industries (oil fields).

2. *Power and engineering*: Water, wind, and animal power (rivers and riparian land); steam and ICE; electricity (public overhead space); engineering and methods of manufacture.

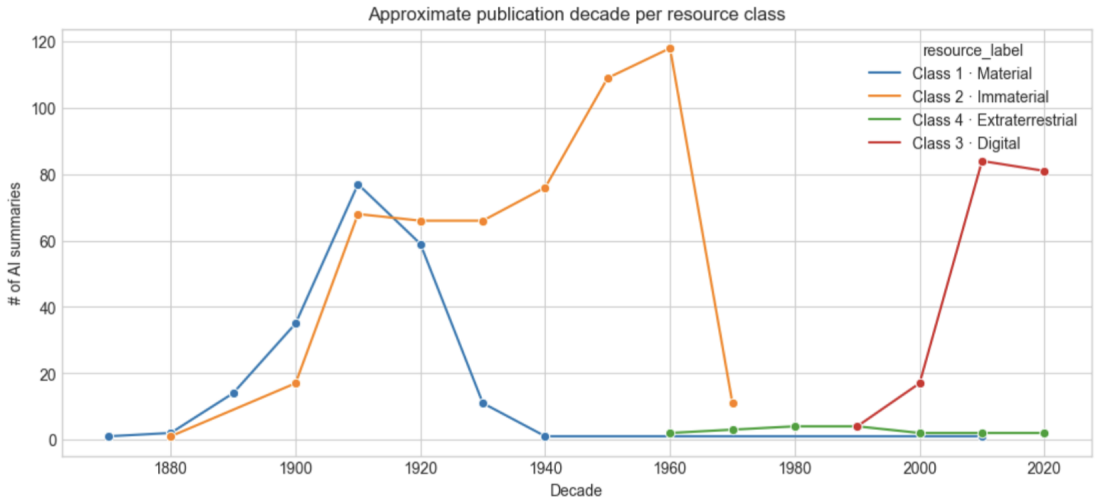
3. *Transport*: Roads, bridges, and vehicles; inland waterways (isthmus of Panama; riparian land); ports and shipping (ocean); rail (frontier land); aeronautics (public airspace); spaceflight (orbits; asteroids).

4. *Communication and calculation*: Language, writing, printing, and graphic arts; information: timekeeping, computing, telecommunications, and audiovisual (data).

5. *Technology and society*: Agriculture (common land; guano islands); textiles and clothing; building and architecture; the domestic interior; public utilities; weapons and armor (uranium deposits).

2.5 The Evolution of Appropriation: Evidence from U.S. Law Reviews

The figure below summarizes evidence from a comprehensive review of articles published in U.S. law reviews. We first identified articles that analyze legal disputes, doc-



trines, or regulatory interventions related to appropriation. We then restricted attention to those articles in which appropriation concerns a specific resource. Finally, we classified each article according to the nature of the underlying resource—material, immaterial, digital, or extraterrestrial—and assigned it to an approximate publication decade.

The figure plots the number of such articles by decade for each resource class. It therefore captures when legal scholarship has focused on appropriation problems associated with different types of resources, rather than the timing of the underlying technological innovations themselves.

Material resources dominate the legal literature on appropriation in the late nineteenth and early twentieth centuries, with a sharp rise around the turn of the century and a peak in the 1910s and 1920s. This period corresponds to intense legal activity surrounding minerals, land, chemicals, and other physical resources, when rapid industrialization outpaced the development of clear property rights. Immaterial resources—such as spectrum, airspace, and other non-physical natural endowments—rise later and become the primary focus of appropriation-related legal scholarship through the mid-twentieth century. The peak around the 1950s and 1960s reflects the growing importance of these resources and the absence, at the time, of settled ownership and regulatory regimes. Digital resources appear almost exclusively in the late twentieth and early twenty-first centuries. Beginning in the 1990s and accelerating sharply thereafter, legal scholarship increasingly focuses on the appropriation of data, information, and digital traces. This surge coincides with technological advances that transformed digital exhaust into a valuable input

well before property rights over data were clearly defined. Finally, articles addressing extraterrestrial resources—such as orbital slots or space-based assets—remain rare but appear only in recent decades. Their presence underscores that straw-into-gold dynamics continue to arise in domains where technology advances faster than institutions.

Overall, the figure documents a systematic shift in the legal frontier of appropriation across resource classes over time. As property rights become established in one domain, appropriation-related conflict and legal attention migrate to new classes of resources.

3 A Model of Straw-into-Gold Innovation

The economy is populated by innovators, a final goods representative firm, and a representative household. Innovators can turn straw into gold. They discover an idea about how to use a previously unrecognized resource for production. A discovery creates a new resource variety j that can be used to produce a new input variety j. At a point in time, the measure of resource and input varieties is A_t. The representative firm uses the inputs to produce the final good consumed by the household.

Unrecognized resources do not have established property rights before they are discovered and turned into an input. As such, they do not trade in markets at the time of discovery and can become contested afterwards. The innovator thus has two options. First, they can choose to appropriate the resource.[3] A member of the representative household may have a claim over the resource. We will call this member a *counterparty* from now on. The counterparty may challenge the appropriating innovator. The dispute over property rights is settled as a result of litigation in the courts or by the government dictating laws and regulations, assigning ownership of the resource. Alternatively, the innovator can attempt to contract, paying the counterparty for the contested resource. After property rights are established either of these two ways, the factor trades in a competitive market at price q_{jt}.

Next, we describe the representative firm and household's decision problems; the investment, production, and appropriation versus contracting decision problems of innovators; and the economy's technologies for contracting and resolving conflicts over property rights.

[3] Appropriation is equivalent to paying a zero price. That is, the price that would have prevailed if a market existed for a resource that had not been turned into a productive input yet.

3.1 Representative Firm and Household

The final good Y_t is produced by a representative firm. The firm demands input varieties y_{jt} and produces with the aggregate production function

$$Y_t = \left(\int_0^{A_t} \left(y_{jt} \right)^{\gamma} dj \right)^{\frac{1}{\gamma}}.$$

The firm maximizes profits

$$\Pi_t = Y_t - \int_0^{A_t} p_{jt} y_{jt} dj,$$

given input prices p_{jt}.

The representative consumer maximizes discounted utility over the consumption of final goods

$$\int_0^{\infty} e^{-\rho t} \frac{(C_t)^{1-\sigma}}{1-\sigma} dt$$

subject to the budget constraint

$$C_t + \dot{a}_t \leq r_t a_t + \int_0^{A_t} q_{jt} X_{jt} dj$$

where a_t is the value of the portfolio of all firms, r_t is the return on the portfolio, and X_{jt} are service flows from ownership of existing resource variety j with price q_{jt}.

3.2 Innovators

The innovator can use all existing resources to discover new resource (and input) varieties — to turn straw into gold. We assume existing resources are perfect substitutes in such investment and the technology is linear. Given investment $\tilde{x}_{it}$ of resource i, the innovator discovers $\dot{A}_t$ new varieties according to

$$\dot{A}_t = \lambda \int_0^{A_t} \tilde{x}_{it} di. \tag{3.1}$$

The assumption of perfect substitutatibility immediately implies that all resources will trade at the same price $q_{it} = q_t$ in equilibrium, so we drop the index i from now on.

Production of input variety j uses the corresponding resource. The production technology is linear: x_{jt} units of the resource delivers

$$y_{jt} = x_{jt}$$

units of the input. The flow profits are

$$\pi_{jt} = \left(p_{jt} - q_t\right) x_{jt}.$$

We assume that the firm sets a price p_{jt} equal to a constant markup μ over marginal cost $p_{jt} = (1 + \mu)\, q_t$. This allows us to easily capture two cases. First, given the representative firm CES production function, the economy with $\mu = \frac{1-\gamma}{\gamma}$ corresponds to the case of monopolistic competition, where $0 < \gamma \leq 1$. Innovators obtain an infinite patent for their differentiated input variety j and charge monopoly prices, as in traditional models of expanding input varieties (Romer, 1994). Second, the economy with $\mu = 0$ corresponds to the case of perfect competition. Other firms cannot be excluded from using the new idea that a previously unknown resource is valuable in production. Such idea is not of a technical nature, so it is not patentable. Nonrivalry implies that the idea diffuses, and the threat of firm entry makes prices fall to marginal cost.

3.2.1 Conflict

After a discovery, the innovator can choose to appropriate the resource with ill-defined property rights. If they do, a counterparty with a potential claim can challenge them. Motivated by our case studies in Section 2, we assume this process takes time and the outcome of the dispute over property rights is uncertain.

The counterparty is initially unaware of the innovation and resource appropriation. They learn at some future point in time; an event that follows a Poisson process with arrival rate δ. The counterparty initiates a dispute at that point. The dispute is resolved in favor of the innovator with probability θ, in which case they keep the resource they have appropriated. Otherwise, ownership goes to the counterparty and, in addition, the innovator must pay ν as a penalty (or in damages) for appropriation. [4] The arrival rate δ and probability θ are exogenous for now. We endogeneize them later when considering the politics of innovation in Section 5.

The rate δ captures how fast it becomes known that an innovation has turned a previously unrecognized resource into a productive input, and that the innovator has appropriated it. In expectation, the innovator enjoys the fruits from appropriation for a period

[4] Conflict is zero-sum under these assumptions. One could have assumed that conflict was costly to society. For example, κ units of the resource could be lost in the process of assigning property rights (e.g., the cost of litigation or implementing regulation). Moreover, resolving conflicts may take time, following a Poisson process with arrival rate α. The rate α would capture how fast institutions are in resolving disputes; for example, disputes make take longer to resolve because courts are sluggish or regulations are slow to be implemented.

of length $1/\delta$ where property rights remain ill-defined. The probability θ captures the extent to which property rights are already somewhat defined beforehand. For example, θ would be higher when court precedent regarding similar disputes have favored the innovator in the past, and θ would be lower when past laws already assign some rights to the public. Alternatively, θ could be higher when the innovation creates a more powerful constituency of consumers that support it, as in Section 5.

In all, choosing to appropriate the resource and resolve the conflict over property rights afterwards creates the chance for extraordinary rents if the dispute is resolved in favor of the innovator. But risks expropriation, penalties, damages, or outright business failure when it does not. Such is the *innovator's gamble*. Formally, the expected value for an innovator that chooses to appropriate a resource and begin producing at time t is

$$\mathcal{V}_{it}^{\text{conflict}} = \mathcal{D}_{it} + \mathcal{R}_t,$$

where

$$\mathcal{D}_{it} \equiv \int_t^\infty e^{-\int_t^s r_v dv} \pi_{is} ds$$

are traditional rents from production of the new input variety, and

$$\mathcal{R}_t \equiv \underbrace{\int_t^\infty e^{-\int_t^s r_v dv} e^{-\delta(s-t)} q_s ds}_{\text{Informational rents}} + \underbrace{\int_t^\infty e^{-\int_t^s r_v dv} \left(1 - e^{-\delta(s-t)}\right) (\theta - (1-\theta)\nu) q_s ds}_{\text{Institutional rents}}$$

are expected rents from appropriation of the new resource. The expression for appropriation rents $\mathcal{R}_t$ shows two sources of rents for the innovator at the time of appropriation t. First, the innovator enjoys *informational rents* because it takes time for the counterparty to become aware of the innovation and the resource appropriation in order to initiate the dispute — a period of length $1/\delta$ in expectation. Second, the innovator enjoys *institutional rents* because they expect to gain $\theta - (1-\theta)\nu$ units of resources at the time of resolution. Institutional rents may be positive or negative, depending on the penalties or damages paid ν and the probability θ of winning the dispute.

For the counterparty, the expected value of initiating the dispute at time s is

$$\mathcal{U}_s^{\text{conflict}} = \int_s^\infty e^{-\int_t^h r_v dv} (1-\theta)(1+\nu) q_h dh,$$

since it favors them with probability $1-\theta$, assigning them ownership of the resource 1 and payment ν.

3.2.2 Contract

Instead of choosing appropriation and conflict, the innovator can attempt to contract with the counterparty and establish property rights beforehand. The innovator offers to pay for the factor to the counterparty, and both parties commit not to re-negotiate or dispute afterwards. Specifically, the contract negotiates a one time payment $\tilde{p}_t$ for the purchase of the resource at time t. The conflict option remains available to both parties — it is their outside option.

The expected value of contracting for the innovator is

$$\mathcal{V}_{it}^{\text{contract}} = \mathcal{D}_{it} + \int_t^{\infty} e^{-\int_t^s r_v dv} q_s ds - \tilde{p}_t.$$

As for the counterparty, they may choose to accept the contract or reject it. The existence of the resource is initially unknown to the counterparty, or equivalently, they believe it is useless. By offering the contract, the innovator reveals to the counterparty that a new resource exists, that it has some productive value, and, importantly, that they may have a claim over it.[5] That is, the innovator gives away the informational rents from the counterparty remaining unaware for some period of time — it is as if the arrival rate was $\delta \to \infty$. In keeping the gambling metaphor, the innovator inevitably *tips their hand* when trying to contract beforehand.

If the counterparty rejects the contract and the gamble is profitable, the innovator would appropriate the resource anyways and settle the conflict over property rights afterwards. That is, whenever $\lim_{\delta\to\infty} V_{it}^{\text{conflict}} \geq 0$ the innovator cannot commit not to appropriate the resource and use it to produce the new input. In this case, the act of offering the contract improves the counterparty's outside option: it gives them the option to reject the contract and resolve the conflict over property rights afterwards, obtaining the expected value $\mathcal{U}_s^{\text{conflict}}$. Otherwise, when the gamble is not profitable, the counterparty's outside option is simply zero; the innovator would never appropriate the resource if the counterparty rejects the contract.

In all, the value of a contract for the counterparty is

$$\mathcal{U}_t^{\text{contract}} = \max\left\{\tilde{p}_t, \mathbb{I}_{\lim_{\delta\to\infty} \mathcal{V}_{it}^{\text{conflict}} \geq 0} \mathcal{U}_t^{\text{conflict}}\right\}.$$

[5] We assume that the information about the counterparty's chance of winning an eventual dispute $1-\theta$ is either common knowledge or it is "hard information" that is credibly disclosed to them. Likewise, the counterparty learns about the true productive value of the resource after being offered a contract, as captured by the stream of profits π_{it} and prices q_{is}. That is, there is no information asymmetry and the counterparty is neither pessimistic nor overoptimistic. Asymmetric information would create additional scope for contracting when the counterparty is pessimistic, and reduce the scope when they are overoptimistic.

3.3 Market clearing

Market clearing in the input market requires that

$$y_{jt} = x_{jt},$$

and in the final goods market

$$C_t = Y_t = \int_0^{A_t} p_{jt} y_{jt} di.$$

Resource j yields a one-unit service flow at each point in time, which can be allocated to producing input j, or innovation. Market clearing in the resource market thus requires

$$x_{jt} + \tilde{x}_{jt} = 1.$$

Lastly, the value of the household's firm portfoilio is

$$a_t = \int_0^{A_t} \mathcal{V}_{jt} dj,$$

where$\mathcal{V}_{jt}$ is the discounted value of profits from input variety j.

4 The Economics of Innovation under Contested Property Rights

Why does conflict arise? Where do the economic rents incentivizing innovation come from? How does this shape innovation and long-run growth? We next turn to answering these questions.

4.1 Conflict or contract?

To develop intuition about the economics of the problem, we begin by considering a partial equilibrium of the model with a constant interest rate r, and where the stream of profits π_{it}, resource prices q_{it} and contract prices $\tilde{p}_s$ grow at a constant rate g. The next section endogeneizes all variables in general equlibrium. In particular, we characterize the equilibrium along a balanced growth path and provide sufficient conditions for conflict to arise.

In partial equilibrium, we obtain the values under conflict

$$\mathcal{V}^{\text{conflict}} = \max\left\{\frac{\pi+q}{r-g} - \frac{\delta}{r-g+\delta}\mathcal{U}^{\text{conflict}}, 0\right\}$$
$$\mathcal{U}^{\text{conflict}} = \frac{1}{r-g}(1-\theta)(1+\nu)q$$

and under contract

$$\mathcal{V}^{\text{contract}} = \max\left\{\frac{\pi+q}{r-g} - \tilde{p}, \lim_{\delta\to\infty}\mathcal{V}^{\text{conflict}}\right\}$$
$$\mathcal{U}^{\text{contract}} = \max\left\{\tilde{p}, \mathbb{I}_{\lim_{\delta\to\infty}\mathcal{V}^{\text{conflict}}\geq 0}\mathcal{U}^{\text{conflict}}\right\}.$$

Figure 3 shows the contract prices $\tilde{p}$ that the innovator is willing to offer (blue region) and the counterparty is willing to accept (red region) as a function of the counterparty's utility under conflict $\mathcal{U}^{\text{conflict}}$. The purple region depicts when contracting arises; outside of this region conflict arises instead.

Consider first the case where $V^{\text{conflict}} < 0$ so that the innovator's gamble is not profitable — $\mathcal{U}^{\text{conflict}}$ is higher than $\frac{r-g+\delta}{\delta}\frac{\pi+q}{r-g}$ in the figure. The counterparty is willing to accept any positive price $\tilde{p} \geq 0$ since their outside option is nil. The innovator is willing to offer any price which makes the innovation profitable under the contract — that is, any $\tilde{p}$ lower than $\frac{\pi+q}{r-g}$ in the figure. As a result, there is always a price at which both parties are willing to contract — the purple region in the figure. Therefore, conflict does not arise and property rights are always established beforehand via contracting.

Consider next the case where $\mathcal{V}^{\text{conflict}} \geq 0$ so that the innovator's gamble is profitable — $\mathcal{U}^{\text{conflict}}$ is lower than $\frac{r-g+\delta}{\delta}\frac{\pi+q}{r-g}$ in the figure. The innovator is now only willing to offer contract prices that are low enough; lower than $\tilde{p} : \mathcal{V}^{\text{conflict}} = \mathcal{V}^{\text{contract}}$ which makes them indifferent — the blue line in the figure. The counterparty's outside option remains nil when $\mathcal{U}^{\text{conflict}}$ is still higher than $\frac{\pi+q}{r-g}$: they accept any positive price $\tilde{p} \geq 0$. The reason is that, if they rejected the contract, the innovator would walk away instead of choosing to innovate under conflict, since $\lim_{\delta\to\infty}\mathcal{V}^{\text{conflict}} < 0$ in this case. Again, there is always a price at which both parties are willing to contract — the purple region in the figure.

Finally, when $\mathcal{U}^{\text{conflict}}$ is lower than $\frac{\pi+q}{r-g}$, the counterparty's outside option improves to $\mathcal{U}^{\text{conflict}}$ because, if they rejected the contract, the innovator would still choose to resolve the dispute over property rights via conflict. Thus, the counterparty only accepts contract prices that are high enough; above the price $\tilde{p} = \mathcal{U}^{\text{conflict}}$ which makes them indifferent — the red line in the figure. In this case, there is no possible contract that the innovator is willing to offer and the counterparty accept. Therefore, conflict arises and

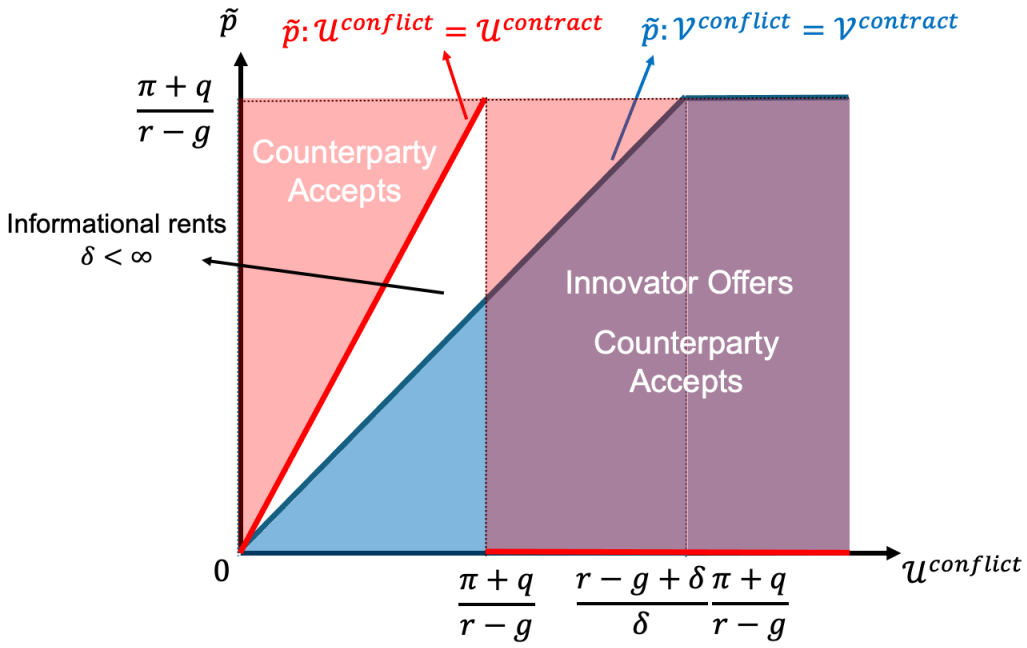


Figure 3: Conflict v. Contract

property rights are established after the time where innovation and appropriation had taken place. The reason is that, by offering the contract, the innovator gives away theyr informational advantage and allows the counterparty to extract some rents. Graphically, the informational advantage just described implies that the indifference line of the innovator — the blue line in the figure — is steeper than that of the counterparty's — the red line. As a result, there is a region where neither the innovator wishes to offer a contract nor the counterparty would accept it — the white region in the figure.

THE ROLE OF INFORMATION REVELATION. Central to conflict arising is the assumption that the act of offering a contract reveals valuable information to the counterparty. That is, that the innovator tips their hand. To see this, suppose that the contract revealed no information about how valuable the new resource was, so the counterparty keeps believing that it is useless — they believe profits π and price q are such that $\pi + q = 0$ and thus expect $\mathcal{V}^{\text{conflict}} = 0$. Then, conflict never arises: the innovator can offer to contract at a zero price $\tilde{p}$ and the counterparty would accept it. Similarly, suppose that $\delta \to \infty$ so that the innovator had no informational advantage. Then, there is always a contract price $\tilde{p} = \mathcal{U}^{\text{conflict}}$ that would parties would agree on.

4.2 Balanced growth path

We now solve for the general equilibrium of our model along a balance growth path (BGP) where: (i) all variables grow at constant rates, (ii) appropriation and conflict delivers positive rents in expectation $\mathcal{R}_t > 0$, and (iii) the contract price is the resource's competitive price $\tilde{p}_t = \int_t^\infty e^{-\int_t^s r_v} q_s ds$.[6]

The following proposition establishes sufficient conditions for conflict or contracting to arise along a BGP, and characterizes the growth rate of varieties g_A in each case. We assume throughout that $\rho < \lambda\mu$ and $\frac{\sigma-1}{\gamma} + 1 > 0$, which guarantee that the growth rate g_A remains positive and that the interest rate r is above the growth rate. We normalize the initial resource price q to 1.

Proposition 1. (Balanced growth path) *If* $(1-\theta)(1+\nu) < 1 + \frac{\left(\frac{\sigma-1}{\gamma}+\frac{\rho}{\lambda}\right)\mu}{\frac{\sigma-1}{\gamma}+1+\mu}$ *and* $\delta < \lambda$*, then conflict arises along a balanced growth path and expected appropriation rents* $\mathcal{R}_t$ *are positive. If* $(1-\theta)(1+\nu) > 1 + \frac{\left(\frac{\sigma-1}{\gamma}+1+\frac{\rho}{\lambda}\right)\mu}{\frac{\sigma-1}{\gamma}+1+\mu}$ *and* $\delta > \lambda$*, then contracting arises along a balanced growth path and the resource's competitive price is in the contracting set.*

The growth rate of varieties is the solution to

$$g_A = \frac{\lambda\left(\mu + \mathcal{R}\left(g_A\right)\right) - \rho}{\frac{\sigma-1}{\gamma} + 1 + \mu}, \tag{4.1}$$

where the expected appropriation rents are

$$\mathcal{R}\left(g_A\right) \equiv 1 - \frac{\delta}{\rho + \delta + \left(\frac{\sigma-1}{\gamma} + 1\right) g_A}(1-\theta)(1+\nu) > 0$$

when conflict arises along a balanced growth path and $\mathcal{R}\left(g_A\right) = 0$ *when contracting does.*

Proof. See Appendix A.1. □

The first part of the proposition shows sufficient conditions for conflict to arise along a balanced growth path, and for appropriation rents to be positive in expectation. Intuitively, this is the case when the probability θ that the innovator wins the dispute over property rights is high enough or the penalty ν is low enough — the counterparty's expected rents $\mathcal{U}^{\text{conflict}}$ are small enough, as illustrated in Figure 3 — and when the rate δ at which counterparties learn about the innovation and appropriation is sufficiently low to

[6] XXX We need to justify why we pick the competitive price. Something like it is a natural outcome of bargaining, supported with some cites. And then also say that it gives the same growth rate as in Romer, which we find convenient for comparison with the literature. XXX

generate large enough informational rents. The second part shows sufficient conditions for contracting to arise, and for the resource's competitive price to be in the contracting set. Again, contracting arises when the counterparty's expected rents $\mathcal{U}^{\text{conflict}}$ are large enough, and the competitive price is feasible when the rate δ is high enough so that the innovator's expected appropiation rents are sufficiently small.

Regarding the growth rate g_A, there are two key equations that characterize innovation and growth. First, optimality of the innovator investments in discovering resource varieties requires that returns to an additional variety are equal to its marginal cost $\lambda \mathcal{V}_t = q_t$. This implies that

$$\lambda \left(\frac{\pi}{q} + \mathcal{R}\left(g_A\right) \right) = \tilde{r}$$

where profits over marginal cost are $\frac{\pi}{q} = \mu x$, and the effective discount rate is $\tilde{r} \equiv r - \frac{\dot{q}_t}{q_t} = \rho + \sigma g_A$ from the household's Euler equation and goods market clearing. Second, the accumulation equation together with market clearing in each resource market implies that the growth rate g_A of varieties is

$$g_A = \lambda \left(1 - x\right).$$

Together, these conditions imply the BGP growth rate g_A in Proposition 1.

4.3 Economic implications

4.3.1 Rents from appropriation of unrecognized resources sustain innovation

From models of expanding input variety (Romer 1990, Jones 1995, 2005) or capital vintages (Jovanovic & Yatsenko, 2010) to models of creative destruction (Aghion & Howitt, 1992; Grossman & Helpman, 1991), traditional models of innovation-driven growth share two key features. First, innovations turn known, existing resources that trade in markets into new input varieties, capital vintages or higher-quality goods. Second, innovations grant firms with rents from production — for example, because of patents over new inputs — that justify their costs.

Equation 4.1 makes these statements precise when contracting arises. In this case, our model reduces to a standard model of expanding input varieties: the growth rate coincides with that of the "lab-model" in Acemoglu XXX. This is a direct consequence of assuming that contracting occurrs at the resource's competitive price; in the standard model, existing resources trade in competitive markets. As result, absent rents from pro-

ducing new inputs — when markups $\mu = 0$ — the economy does not innovate nor grows in the long-run.

In the case of straw-into-gold innovation, however, innovation turns previously unrecognized resources into new input varieties, and traditional rents are not required to sustain long-run growth. Instead, expected rents $\mathcal{R}$ from appropriating unrecognized resources may suffice. As shown in expression 4.1, even when markups $\mu = 0$, the prospect of securing ownership over the resource is enough to generate positive long-run growth $g_A > 0$. In all, we find that economic rents from appropriation of resources can sustain innovations that turn straw into gold, beyond traditional rents that have been the focus of a large literature.

4.3.2 Property rights emerge as a consequence of innovation

Much work emphasizes the cost of insecure property rights for economic growth (Coase, 1960; North, 1981; Engerman and Sokoloff, 2005; Acemoglu and Johnson, 2005; Hornbeck, 2010). In particular, well-established property rights over ideas and new products are thought to be a pre-condition for innovation.

When it comes to straw-into-gold innovation, firms innovate precisely because property rights over unrecognized resources are ill-defined — expecting rents from appropriation — and property rights emerge as a consequence of innovation, not a cause. Formally, there is a period time — of length $1/\delta$ on average — where property rights remain ill-defined after innovation and appropriation have taken place, but before a counterparty learns about them and initiates a dispute. Property rights become established only after the dispute is resolved. Thus, the state does not only protect property rights over ideas and new inputs, it allocates property rights over unrecognized resources as well.

4.3.3 Higher growth is associated with appropriation and conflict

A natural question is whether larger appropriation rents — from a higher likelihood of success θ, lower penalties ν, or lower learning rate δ — leads to a higher long-run growth rate g_A. Since Proposition 1 shows that a high θ implies that conflict will arise in equilibrium, this would imply that conflict comes hand and in hand with higher innovation and economic growth.

4.3.4 Unrecognized resources differ from imperfectly protected ideas

5 The Politics of Innovation under Contested Property Rights

5.1 Optimal policy (preliminary and incomplete)

Household utility along a balanced growth equilibrium is

$$U = \frac{1}{1-\sigma} \frac{\left(1 - \left(\frac{1}{\lambda} + \kappa\right) g_A\right)^{1-\sigma}}{\rho + \frac{\sigma-1}{\gamma} g_A},$$

where we have normalized the initial number of varieties to 1. A higher growth rate thus increases future consumption, but crowds-out current consumption becauses of resources spent in discovering new varieties — cost $\frac{1}{\lambda}$ — and resolving conflicts — cost κ. The optimal growth rate balances these forces

$$g_A^* = \frac{1}{\sigma} \left(\frac{1}{\frac{1}{\lambda} + \kappa} - \rho\gamma \right).$$

How can a government implement the optimal growth rate? Suppose that a government control how linient the courts are towards innovators that appropriate resources with contested property rights. That is, they choose the probability θ of innovators' winning a dispute or the penalties ν. Then, the optimal growth rate is implemented by setting

$$(1-\theta)(1+\nu) = \left(\mu - \frac{1-\gamma}{\gamma}\right) \left(1 - \frac{1}{\sigma}(\lambda - \gamma\rho)\right) \frac{\rho + \delta + \left(\frac{\sigma-1}{\gamma} + 1\right) \frac{1}{\sigma}(\lambda - \gamma\rho)}{\delta},.$$

The case of monopolistic competition $\mu = \frac{1-\gamma}{\gamma}$ implies that $\theta^\star = 1$ is *exactly* optimal — the government should allow full appropriation. An economy with even lower markups (as with perfect competition $\mu = 0$) implies a corner solution with $\theta^\star = 1$ if $\sigma \geq 1 - \frac{\rho\gamma}{\lambda}$. Otherwise, there is an interior solution $\theta^\star < 1$ if $\sigma < 1 - \frac{\rho\gamma}{\lambda}$ or if markups are higher than under monopolistic competition $\mu > \frac{1-\gamma}{\gamma}$.

5.2 Shaping the coercive power of the state

Innovators have strong incentives to shape how the state's coercive power is applied (to increase θ). In earlier eras this meant influencing the use of force; today it more often means steering litigation outcomes, legislation, and regulation — raising the likelihood

that policy tilts in their favor.

They can pursue this through lobbying, regulatory capture, or the "traffic of influence," tactics that may secure advantageous rules but risk being socially wasteful. Another route is to redirect the trajectory of innovation itself so that it better serves influential constituencies and aligns with public objectives, making the firm more likely to win favor from state actors.

These strategies can be genuinely useful if they expand consumer surplus — say, by lowering markups μ. Yet they also carry dangers. When firms tailor technology to government priorities, they may render it more relevant to state power, including in dual-use applications that blur civilian and military or surveillance purposes.

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Online Appendix for: Turning Straw into Gold

This online appendix contains the proofs and derivations of all theoretical results for the article "Turning Straw Into Gold."

Any references to equations, figures, tables, assumptions, propositions, lemmas, or sections that are not preceded "A.," "B.," "C.," "D.," "E." or "F." refer to the main article.

A Proofs and Derivations

A.1 Poof of Proposition 1

We consider a symmetric equilibrium and drop all i indices from now on. Firm profits are

$$\pi_t = \mu \left(1+\mu\right)^{-\frac{1}{1-\gamma}} \left(q_t\right)^{-\frac{\gamma}{1-\gamma}} C_t,$$

and the first order conditions for the representative firm and household are

$$\begin{aligned} c_t &= \left(p_t\right)^{-\frac{1}{1-\gamma}} C_t \\ 1 &= A_t \left(p_t\right)^{-\frac{\gamma}{1-\gamma}} \\ r_t &= \rho + \sigma \frac{\dot{C}_t}{C_t}, \end{aligned}$$

where we have normalized the price of aggregate consumption good to 1.

Innovator's optimal investment implies that the price of all factor varieties are equalized $q_{it} = q_t$ and that the returns to an additional variety are equal its marginal cost

$$\lambda \mathcal{V}_t = q_t.$$

The market clearing conditions are

$$\begin{aligned} a_t &= A_t \mathcal{V}_t \\ 1 &= \tilde{x}_t + x_t \\ c_t &= x_t \\ \dot{A}_t &= \lambda A_t \tilde{x}_t. \end{aligned}$$

Next, we solve for the balanced growth path. We denote by g_q, g_A,and g_C the growth rates of factor prices q, varieties A, and consumption C along a BGP. We normalize the

price level $q = 1$. The equilibrium conditions result in

$$\begin{aligned}
1 &= A\left(1+\mu\right)^{-\frac{\gamma}{1-\gamma}} \\
g_A &= \frac{\gamma}{1-\gamma} g_q \\
x &= \left(1+\mu\right)^{-\frac{1}{1-\gamma}} C \\
g_C &= \frac{1}{1-\gamma} g_q \\
r &= \rho + \sigma g_C \\
1 &= \lambda \mathcal{V} \\
g_A &= \lambda\left(1-x\right) \\
\pi &= \mu x
\end{aligned}$$

Moreover, when the contracting price is the competitive price $\tilde{p} = \frac{1}{r-g_q}$ and given expected rents from appropriation

$$\mathcal{R} = 1 - \frac{\delta}{r - g_q + \delta}\left(1-\theta\right)\left(1+\nu\right),$$

we can write the value for the innovator as

$$\mathcal{V} = \frac{\pi + \mathbb{I}_{\text{conflict}}\mathcal{R}}{r - g_q}.$$

Together, with the innovator's optimality condition, the above implies that the growth rate of varieties is the solution to

$$g_A = \frac{\lambda\left(\mu + \mathcal{R}\left(g_A\right)\right) - \rho}{\frac{\sigma-1}{\gamma} + 1 + \mu},$$

where $\mathcal{R}\left(g_A\right) = 1 - \frac{\delta}{\rho+\delta+\left(\frac{\sigma-1}{\gamma}+1\right)g_A}\left(1-\theta\right)\left(1+\nu\right)$ in the case of conflict and $\mathcal{R}\left(g_A\right) = 0$ in the case of contracting.

A.1.1 Sufficient conditions for conflict with positive appropriation rents

We have shown in Section 4.1 that conflict arises if and only if the following inequality holds

$$\left(r-g\right)\mathcal{U}^{\text{conflict}} \equiv \left(1-\theta\right)\left(1+\nu\right) < \pi + 1.$$

Moreover, there are positive appropriation rents $\mathcal{R}(g_A)$ if and only if

$$\mathcal{R}(g_A) \equiv 1 - \frac{\delta}{\rho + \left(\frac{\sigma-1}{\gamma} + 1\right) g_A + \delta} (1-\theta)(1+\nu) \geq 0.$$

Using the expression for the $\mathcal{V}$ and the fact that $1 = \lambda \mathcal{V}$, these are equivalent to

$$(1-\theta)(1+\nu) < \frac{\rho + \left(\frac{\sigma-1}{\gamma} + 1\right) g_A + \delta}{\lambda}$$
$$(1-\theta)(1+\nu) \leq \frac{\rho + \left(\frac{\sigma-1}{\gamma} + 1\right) g_A + \delta}{\delta}$$

Therefore, if $\delta < \lambda$, then the first inequality immediately implies that the second one holds, so there are positive appropriation rents $\mathcal{R}(g_A) > 0$. Lastly, using that $\pi = \mu \left(1 - \frac{1}{\lambda} g_A\right)$, we can write the first inequality as

$$(1-\theta)(1+\nu) < \mu \left(1 - \frac{1}{\lambda} g_A\right) + 1.$$

Using that $g_A \leq \frac{\lambda(\mu+1)-\rho}{\frac{\sigma-1}{\gamma}+1+\mu}$,a sufficient condition for the inequality to hold is

$$(1-\theta)(1+\nu) < \mu \frac{\frac{\sigma-1}{\gamma} + \frac{\rho}{\lambda}}{\frac{\sigma-1}{\gamma} + 1 + \mu} + 1.$$

A.1.2 Sufficient conditions for contracting at the resource's competitive price

Contracting arises if

$$\left(r - g_q\right) \mathcal{U}^{\text{conflict}} \equiv (1-\theta)(1+\nu) > \pi + 1$$

and the resource's competitive price $\tilde{p} = \frac{1}{r - g_q}$ is in the contracting set if

$$\frac{\delta}{r - g_q + \delta} (1-\theta)(1+\nu) \geq 1.$$

Using the expression for $\mathcal{V}$ and the fact that $1 = \lambda\mathcal{V}$, these are equivalent to

$$(1-\theta)(1+\nu) > \frac{\rho + \left(\frac{\sigma-1}{\gamma}+1\right)g_A + \lambda}{\lambda}$$
$$(1-\theta)(1+\nu) \geq \frac{\rho + \left(\frac{\sigma-1}{\gamma}+1\right)g_A + \delta}{\delta}.$$

Therefore, if $\delta > \lambda$, the first inequality implies that the second is satisfied too. Moreover, replacing with the BGP growth rate g_A, we have that the first inequality becomes

$$(1-\theta)(1+\nu) > \mu\frac{\frac{\sigma-1}{\gamma}+1+\frac{\rho}{\lambda}}{\frac{\sigma-1}{\gamma}+1+\mu}+1.$$

A.2 Additional results

A.2.1 Conflict helps turn straw into gold

We have that g_A is the solution to

$$1 = \lambda \max\left\{\frac{V^{\text{contract}}}{q}, \frac{V^{\text{conflict}}}{q}\right\}.$$

Using the expressions for $V^{\text{contract}}$and V^{conflict} derived above, this is equivalent to

$$\rho + \left(\frac{\sigma-1}{\gamma}+1\right)g_A = \lambda \max\left\{\frac{\delta}{\rho + \left(\frac{\sigma-1}{\gamma}+1\right)g_A + \delta}\left(1 - \frac{\mu}{\lambda}g_A + \mu - \frac{\tilde{p}}{q}\right), 1 - \mu\frac{1+\lambda\kappa}{\lambda}g_A + \mu + (\theta -$$

Note that the left-hand-side is striclty increasing in g_A and independent of θ. We next show that the right-hand-side is strictly decreasing in g_A and weakly increasing in θ.

First note that this obviously true in the branch where $V^{\text{contract}} \leq V^{\text{conflict}}$ and so the right-hand-side is simply $\lambda\left(1 - \mu\frac{1+\lambda\kappa}{\lambda}g_A + \mu + (\theta-1)(1+\kappa)\right)$. Thus, this holds when either θ is high enough that $V^{\text{contract}} \leq V^{\text{conflict}}$ or when the contracting price is at is upper bound so that $V^{\text{contract}} = V^{\text{conflict}}$. Suppose instead the solution to g_A is under the branch where $V^{\text{contract}} > V^{\text{conflict}}$ and so the right-hand-side is $\lambda\frac{\delta}{\rho+\left(\frac{\sigma-1}{\gamma}+1\right)g_A+\delta}\left(1 - \frac{\mu}{\lambda}g_A + \mu - \frac{\tilde{p}}{q}\right)$. We have two cases. If $\frac{\tilde{p}}{q}$ is constant for any possible θ so that $\frac{\tilde{p}}{q}$ is stricly lower than its upper bound and strictly larger than its lower bound, then the right-hand-side is decreasing in g_A and insensitive to θ. If $\frac{\tilde{p}}{q}$ is at its lower bound so that $\tilde{p} = \max\left\{\frac{(1-\theta(1+\kappa))q}{\rho+\left(\frac{\sigma-1}{\gamma}+1\right)g_A}, 0\right\}$,

then the right-hand side is again strictly decreasing in g_A but weakly increasing in θ. In all, this shows that the right-hand-side is strictly decreasing in g_A and weakly increasing in θ.

Finally, it must be that the equilibrium growth rate g_A^* is weakly increasing in θ because the left-hand-side is striclty increasing in g_A and independent of θ, whereas the right-hand-side is strictly decreasing in g_A and weakly increasing in θ.

A.2.2 Optimal Policy

Household utility is

$$\begin{aligned} U &= \int_0^\infty e^{-\rho t} \frac{\left(C_0 e^{g_C t}\right)^{1-\sigma}}{1-\sigma} dt \\ &= \frac{(C)^{1-\sigma}}{1-\sigma} \int_0^\infty e^{-\left(\rho + \frac{\sigma-1}{\gamma} g_A\right) t} t dt \\ &= \frac{A^{\frac{1-\sigma}{\gamma}}}{1-\sigma} \frac{\left(1 - \frac{1}{\lambda} g_A\right)^{1-\sigma}}{\rho + \frac{\sigma-1}{\gamma} g_A}. \end{aligned}$$

Therefore, the optimal growth rate is

$$g_A^* = \frac{1}{\sigma} (\lambda - \gamma\rho)$$

which is implemented with

$$\theta^* = 1 - \frac{1}{1+\kappa} \frac{1}{\sigma} \left(\frac{\rho\gamma}{\lambda} + \frac{\sigma - 1}{1 + \lambda\kappa} \right) \left(\mu (1 + \lambda\kappa) - \frac{1-\gamma}{\gamma} \right) - \frac{1}{1+\kappa} \frac{\lambda\kappa}{1+\lambda\kappa}.$$

$$(1-\theta)(1+\nu) = \left(\mu - \frac{1-\gamma}{\gamma} \right) \left(1 - \frac{1}{\sigma} (\lambda - \gamma\rho) \right) \frac{\rho + \delta + \left(\frac{\sigma-1}{\gamma} + 1 \right) \frac{1}{\sigma} (\lambda - \gamma\rho)}{\delta},$$

$$(1-\theta)(1+\nu) = \left(\frac{1}{\gamma} - \frac{\lambda^{\frac{1}{\gamma}}}{\lambda} \right) \frac{\rho + \delta + \left(\frac{\sigma-1}{\gamma} + 1 \right) \frac{1}{\sigma} (\lambda - \gamma\rho)}{\delta}$$

where $\mathcal{R}(g_A) = 1 - \frac{\delta}{\rho + \delta + \left(\frac{\sigma-1}{\gamma} + 1 \right) g_A} (1-\theta)(1+\nu)$

B McNeil's Encyclopedia

Materials

- *Non-ferrous metals (deep sea minerals)*: For centuries, the ocean floor was an unseen expanse. With modern dredging and deep-sea mining technologies, polymetallic nodules containing copper, nickel, and cobalt are now treated as resources. Their appropriation has sparked disputes under the UN Convention on the Law of the Sea, with debates over whether seabed minerals are the "common heritage of mankind" or subject to national and corporate claims.

- *Ferrous metals (aboriginal land in Australia)*: Iron ore discoveries in the 20th century transformed remote aboriginal territories into some of the world's richest mining frontiers. Land once valued primarily for cultural or spiritual purposes became a contested factor, leading to conflicts between mining companies, indigenous communities, and the state over rights and royalties.

- *Chemicals and allied industries (oil fields)*: Petroleum was once a nuisance contaminant in salt wells. With the invention of drilling and refining, underground reservoirs became a vital factor of production. The absence of clear property rights produced the "Rule of Capture" in the U.S., fueling a chaotic oil rush and decades of litigation over who truly owned migrating hydrocarbons.

Power and Engineering

- *Water, wind, and animal power (rivers and riparian land)*: Harnessing water mills, windmills, and animal labor transformed natural flows into mechanical energy. Rivers in particular became contested as navigable waterways, with courts and legislatures ruling on the balance between private riparian rights and public access for mills, canals, and commerce.

- *Steam and Internal Combustion Engines*: Steam engines and later ICEs turned coal and petroleum into vast new factors of production. Once inert minerals buried underground, these fuels became fiercely contested, with mining concessions and drilling rights sparking global conflicts and colonial competition.

- *Electricity (public overhead space)*: With Edison's and Westinghouse's systems, the space above city streets — once ignored — became a critical infrastructure channel for power lines. The chaos of overhead wires in cities like New York led to public

outcry, litigation, and eventually legislation about whether the air above streets was a public or private resource.

- *Engineering and Manufacture*: Standardized methods like interchangeable parts and the assembly line turned organizational knowledge itself into a productive factor. Factories became arenas of contestation over intellectual property, labor control, and the boundaries of trade secrets.

Transport

- *Roads, bridges, and vehicles*: Roads were initially communal pathways, but the rise of toll roads, turnpikes, and bridges converted them into revenue-generating assets. Disputes emerged over toll rights and public versus private ownership of infrastructure essential for commerce.

- *Inland waterways (isthmus of Panama; riparian land)*: The engineering of canals across Panama and Suez turned geographic chokepoints into global factors of production. Control over these waterways became the object of international treaties, wars, and transfers of sovereignty.

- *Ports and shipping (oceans)*: Oceans, once an unregulated commons, became contested through navigation acts, colonial empires, and later the UN Convention on the Law of the Sea, which sought to regulate fishing rights, shipping lanes, and undersea resources.

- *Rail (frontier land)*: Railroads turned frontier land into a productive factor by connecting it to markets. Land grants to rail companies in the U.S. fueled massive speculation and conflicts with indigenous peoples, farmers, and settlers.

- *Aeronautics (public airspace)*: The invention of the airplane transformed the sky into an essential factor. Early disputes concerned whether landowners controlled the air above their property, eventually leading to the principle that navigable airspace was public.

- *Spaceflight (orbits; asteroids)*: Satellites converted orbital space into a valuable production factor. The most desirable orbital slots, particularly geostationary orbit, became scarce and contested, regulated by the ITU amid disputes like the Bogotá Declaration. Future asteroid mining raises similar questions about ownership of celestial bodies.

Communication and Calculation

- *Language, writing, printing, and graphic arts:* The printing press turned words and symbols into mass-producible commodities. Control over printing rights and censorship regimes made language itself a contested factor, leading to struggles between printers, authors, and the state.

- *Information (timekeeping, computing, telecommunications, audiovisual)*: Mechanical clocks, telegraphs, telephones, and later computers all turned intangible flows of information into factors of production. Ownership disputes arose around spectrum allocation, patent monopolies, and more recently, consumer data — as seen in digital advertising and AI.

Technology and Society

- *Agriculture (common land; guano islands)*: The enclosure of common lands in Europe turned previously communal fields into private factors, fueling both agricultural productivity and social upheaval. Similarly, 19th-century claims over guano islands transformed bird excrement into a strategic fertilizer, provoking international disputes.

- *Textiles and clothing*: Industrial spinning and weaving turned cotton and wool into factors whose global supply chains depended on contested land and labor — from enslaved labor in the American South to colonial plantations in India.

- *Building and architecture*: Stone, clay, and timber had long been raw materials, but urbanization turned quarrying rights and land for construction into contested factors, regulated through zoning laws and property regimes.

- *Domestic interior*: Household technologies — stoves, plumbing, electricity — turned private domestic space into a factor of economic growth. Contests emerged around standards, patents, and monopolization of new home appliances.

- *Public utilities*: Water, sewage, gas, and electricity provision turned natural flows into managed urban factors. Fierce disputes arose over municipalization versus private franchise ownership, often decided in city councils and courts.

- *Weapons and armor (uranium deposits)*: With nuclear technology, uranium deposits became a strategic factor of production. Their control became subject to state mo-

nopolization, secrecy, and international treaties such as the Non-Proliferation Treaty, reflecting their contested role in global security.