The Coordination of Independently-Owned Vacuum Tube Patents in the Early Radio Alleged Patent "Thicket"

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Abstract

A popular theory is that it may be sufficiently difficult to reach agreement on patent license terms that holdup in development may occur. Early U.S. radio development is widely believed to provide an empirical example of such holdup during 1905-1920, with numerous allegations of an impasse in bargaining the necessary patent rights until these were ultimately incorporated in the RCA patent pool. This paper seeks to determine with new precision how entrepreneurs and managers actually managed patent rights in this scenario. Accordingly, we re-examine the legal trajectories and entrepreneurial exploitation of patents on early vacuum tube technology where Fleming's diode patent was alleged to have "overlapped" with De Forest's triode patents. We show, by means of the relevant historical record, patent claims, litigation records and other relevant law, how patent rights were resolved by the courts and by the immunity of suppliers to the government from patent infringement liability. We trace the cross-licensing agreements between the different radio interests and find that licensing was always chosen over holdup and so enabled robust, state-of-the-art radio development. **Full text available at** http://j.mp/Radio-Thicket.

Keywords: Patent thicket, Overlapping patents, Anticommons, Holdup, Deadlock, Impasse, Radio, Vacuum tube, Diode, Triode, Marconi, De Forest, Fleming, RCA.

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1. Introduction

Patents have long been sold or licensed by inventors to facilitate exploitation of their inventions. This "market for technology" allowed inventors to specialize in invention while others specialized in the development of their inventions (Lamoreaux et al., 2013, p119). For half of Khan and Sokoloff's list of "great US inventors", sale and license rather than development and product sales were the means by which they extracted much of the income from their inventions (Khan and Sokoloff, 2004, p398). A more complex distribution of rights pertains when patent rights needed to make commercially-viable products are diversely-held by multiple parties, or when patent claims held by separate patentees cover overlapping subject matter, requiring licensing and coordination among such patentees. Such distributions of rights have come to be called patent "thickets" (Teece, 1987). Today the widespread metaphor "patent thicket" may connote substantially different economic conditions (Egan and Teece, 2015): (a) diversely-held complementary inputs; (b) overlapping patents; (c) a gaming of the patent system; and (d) saturated invention spaces. In this study, the alleged radio patent "thicket" consists of the first two categories above.

Some have theorized that there is a possibility of economic "holdup" in the patent thicket: the negotiation of licenses and sales of rights at mutually acceptable prices will prove sufficiently difficult that economic harm in the form of delayed or stifled development may occur.[1]

Such views are important because they appear to have influenced court decisions to weaken the enforcement of patent rights despite a finding of infringement and despite the

[1] There are many metaphors used to characterise the scenario of continued development in the context of multiple, important patent rights held by multiple independent owners but it is common to raise the theoretical possibility that this context increases the chance of some form of development holdup. See for example the *"…patent thicket:* an overlapping set of patent rights" (Shapiro, 2001, p119); the possibility of "Patent Holdup and Royalty Stacking" (Lemley and Shapiro, 2007); it has been called an "anticommons" (Heller and Eisenberg, 1998, p698); similarly with "fragmented invention" (Hall and Harhoff, 2012, p11).

questionable value of some of the assumptions of the patent-holdup models.[2] A concern with the possibility of some kind of holdup is cited as a motivating factor in the many recent proposals to (further) reform the U.S. patent law.[3] If it could be shown that there exist robust empirical cases illustrating patent-induced development holdup there would be important evidence in support of patent law reform. The quid pro quo is that if such cases cannot be found there is no case for change.

The early radio industry attracted our detailed attention, first, because the Fleming patent on the vacuum tube diode and De Forest's patents on the vacuum tube triode[4] constitute a widely-alleged example of patents within a patent thicket which resulted in development block. Second, this was a patent-intensive industry in which there are known to have been many pioneer patents, independently-held and with no close substitutes and there are statements in the literature that prior to the formation of RCA there was a failure in bargaining over the rights under these patents that caused a "deadlock" for development (Brady, 1922, p277). We review the evidence on how a prospective holdup in radio development was resolved and marshal new primary and secondary evidence which clearly shows that the relevant parties arrived at satisfactory resolution without ever reaching the alleged "deadlock". We conclude with a discussion of the implications of our findings and an assessment of our contribution to the growing body of empirical evidence that rebuts the "empirical cases" *purported* to demonstrate patent hold-up.

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[2]. *See*, e.g. *Ultramercial, Inc. v. Hulu, LLC*, 772 F.3d 709 (Fed. Cir. 2014) ("Subject matter eligibility challenges provide the most efficient and effective tool for clearing the patent thicket, weeding out those patents that stifle innovation and transgress the public domain."); See discussion of influence on court decisions in Elhauge (2008, p535-537) and more generally for a critique of holdup model assumptions (Elhauge, 2008).

[3] See Federal Trade Commission discussion of possibility of holdup (2003, p29-30, p41, p55-56) available at; FTC 2003 To Promote Innovation; also (Federal Trade Commission, 2011) available at; FTC 2011 Evolving IP Marketplace

[4] De Forest's term for his device was the "audion;" the "triode" was a later term that captures the distinguishing physical feature of the device that it had three electrodes enclosed within its glass vessel: triode is the term used in this paper.

2. The origin of the alleged patent thicket in the early radio industry

Marconi Wireless Telegraph Company of America, the owner of the Fleming diode patent, U.S. Pat, No. 803,684, asserted it against Lee De Forest, the inventor of the vacuum tube triode, and in 1916 a district court in New York upheld the Fleming patent's validity, with scope reduced to radio frequency (RF) detection, and ruled that the De Forest triode infringed it when used as RF detector. *Marconi Wireless Tel. Co of America v. De Forest Radio Tel. and Tel. Co.*, 236 F. 942, 946 (S.D.N.Y. 1916), *affirmed* 243 F 560 (2nd Cir. 1917), hereafter *Marconi*.

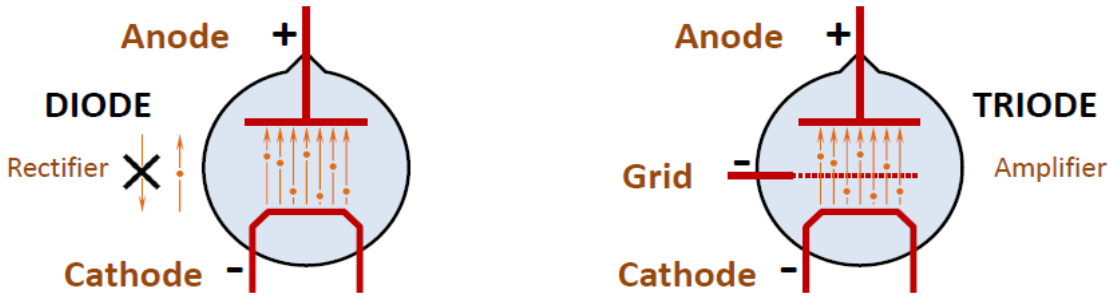

Figure 1. Vacuum tube technology implemented as diode and triode: both implementations consist of an evacuated glass tube with an anode and a cathode, the triode has the "grid", an additional control electrode.

Those who were superficially informed of this decision were apparently drawn to a seductively plausible narrative owing to the apparent physical instantiation of an "overlap" of the diode and triode features as shown in Figure 1: because all elements of Fleming's diode (heated cathode and an anode sealed in a vacuum vessel) are found in De Forest's triode, the diode patent appeared to have covered, or "overlapped," the features of the triode. As we show below, this reading of the court's decision is erroneous. That error was propagated with the added imprimatur of a government agency by the 1924 Federal Trade Commission (FTC) report on radio:

> "[T]he court holding that the Fleming patent dominated the use of a vacuum tube *either as a detector, repeater, amplifier, or oscillator* [our italics]. As a result of this decision the De Forest Co. ceased manufacturing vacuum tubes in their improved form and the Marconi Co. was limited to the manufacture of the two-element tube, which was incapable of performing all the functions of the modern vacuum tube." (Federal Trade

Commission, 1924, pp26).

Indeed, this erroneous narrative that the Fleming diode patent "dominated" the use of vacuum tube repeaters, amplifiers, or oscillators has become an embedded "truth" in the historical literature. Maclaurin has been a particularly influential source for other historians and stated:

> 'The court decided that De Forest had infringed the two-element Fleming vacuum tube, while Marconi had infringed the three-element De Forest patent. Neither company could manufacture the triode' (Maclaurin, 1971, p85).[5]

Had the FTC and Maclaurin's statements been factually correct, one should expect to have seen no triode manufacturing until the putative "deadlock" had been overcome by the pooling of radio patents through the formation of the Radio Corporation of America (RCA). We note at this point that Maclaurin's statement is not specific about which claims of the diode patent were infringed. Furthermore, the claims of the Fleming diode patent *as originally issued* were drawn such that they would conceivably encompass commercial implementations of the De Forest triode patents: this appeared to some historians to be a litigated case of an "overlapping patent" with the diode patent overlapping potential downstream implementations of the triode. This ingrained but erroneous notion influenced at least one author to speculate that the supposed patent "logjam" delayed radio development by as much as 10 years:

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[5] Three other post-1945 historians of radio cite *Maclaurin's* narrative of the 1916 decision rather than the true content of the decision itself: Douglas cites Aitken, and Aitken and Reich cite Maclaurin (Aitken, 1985, p248, Douglas, 1987, p289, Reich, 1977, p216, Reich, 1985, p220). A fifth, the Naval communications historian Howeth, cites the decision directly but expresses the same interpretation, "Neither Marconi nor De Forest nor any other company could legally manufacture the badly needed three-element tube without the mutual consent of the two interested parties" (Howeth, 1963, p374). A sixth, early radio history by Archer quotes (an irrelevant section) from the 1916 decision and mischaracterizes the decision as follows; "The conclusion was that the deForest [sic] invention had infringed that of Fleming, hence that he could not manufacture the three-electrode [triode] without the consent of the Marconi Company… since it included two elements of the Fleming patent" (Archer, 1938, p135). Finally, legal scholars have accepted and cited to these early errors: Kitch cites Maclaurin's interpretation of the decision (Kitch, 1977, p269); Merges and Nelson cite the FTC report (Merges and Nelson, 1990, p892); Merges cites to Reich's 1985 book (Merges, 1994, p85-87); and Grindley and Teece cite Archer, Douglas and Maclaurin (Grindley and Teece, 1997, p11).

> "Not until 1919, when RCA was formed (at the urging of the Navy) to break the patent logjams besetting the industry, was the impasse finally resolved. … the parties haggled for over ten years on the tube-triode bargain alone. ... up to ten years of delay was no doubt quite costly; perhaps FM broadcasting, which was not invented until the 1930s, would have appeared sooner." (Merges, 1994, p85-87).

The focal question of this paper, therefore, is what influence did the diode patent have on technological and commercial downstream development of vacuum tube technology and electronics? In our answer we pay special attention to how the evidence bears on the notion of a patent "logjam" or "thicket" and how development of vacuum tube technology proceeded. In practice we: search for reviews of the technology at issue as published close in time to the events of interest; we seek primary source information on patenting rate of vacuum tube devices and circuits, information contained in patent specifications, their claims, and relevant court decisions. Furthermore, secondary accounts often neglect information on licensing and such information is known to be often difficult to collect because licensing contracts remain private. (Kitch, 2000). We therefore conduct a wide search for evidence of licensing of the pioneer patents at issue.

3. Development of the Triode and Licensing of the Diode Patent

3.1 Development of vacuum tube technologies as radio detectors

The Marconi Company's Fleming vacuum tube diode patent, U.S. Pat. 803,684 was issued November 7, 1905, fully ten years before suit was brought against De Forest's commercial triode product. De Forest's first vacuum tube triode patent U.S. Pat. No. 841,387 on the amplification property of the triode issued January 1907, over eight years earlier than the commencement of Marconi's suit in 1915. We begin with an account of vacuum tube technology development and the exercise of these patent rights in the years leading up to the suit.

We note that court documents can be important records of a technology's market significance and that when the US government was sued for compensation for its unlicensed use of the Fleming diode in the Court of Claims, the Court, as part of its

assessment of the technological significance of this patent made an analysis of the market for the Fleming vacuum tube detector. It found that the Fleming diode tube "did not go into any extended commercial use, only about 700 Fleming [vacuum tubes] having been shipped by [Marconi] to anyone between 1910 and 1915." Moreover, the Court found that some of the many crystal detectors then in use were "much more effective than the Fleming apparatus." *Marconi Wireless Co. v. US,* 81 Ct. Cl. 671, 783 (Ct.Cl. 1935). This statement probably refers to the Dunwoody carborundum crystal detector, for according to Morse's review, the Dunwoody detector was the *best* detector before the advent of the effective triode technology. Furthermore, it is telling that it was the *Marconi Company* that used these crystal detectors and exclusively for transatlantic services and radio-equipped ships in preference to its patented diode vacuum tube detector technology; the crystal detectors remained in use into the 1920s (Morse, 1925, p36, Morse, 1943, p636). Marriott's 1917 paper reviewing diffusion of different radio technologies in the US to1915, confirms this picture. Marriott charts the growth and decline of several detector technologies and describes how in response to patent assertions, non-infringing inventions were developed, such as the crystal detectors that were a design-around electrolytic detector patents and the loop antenna that supplemented another patented antenna (Marriott, 1917, p93). The Fleming vacuum tube patent does not feature in Marriott's account (Marriott, 1917, p184). The Fleming diode detector was a minor technology in competition with superior substitutes and not even favored for important uses by its owner, the Marconi Company.

Improvements in diode vacuum tube performance came about only when general improvements in tube technology, for diode *and* triode applications, were made years after Fleming's 1905 diode patent. These improvements came about when technologies for high vacuum were developed and when cathode temperatures were reduced, first by thoriated-tungsten filaments and eventually by oxide coated unipotential cathode (Thackeray, 1983). Marriott *does* describe the late rise in importance of De Forest's triode detector (the

"Audion"): it was used "in very small numbers until about 1912" when it began displacing the "tikker" detector (Marriott, 1917, p184).

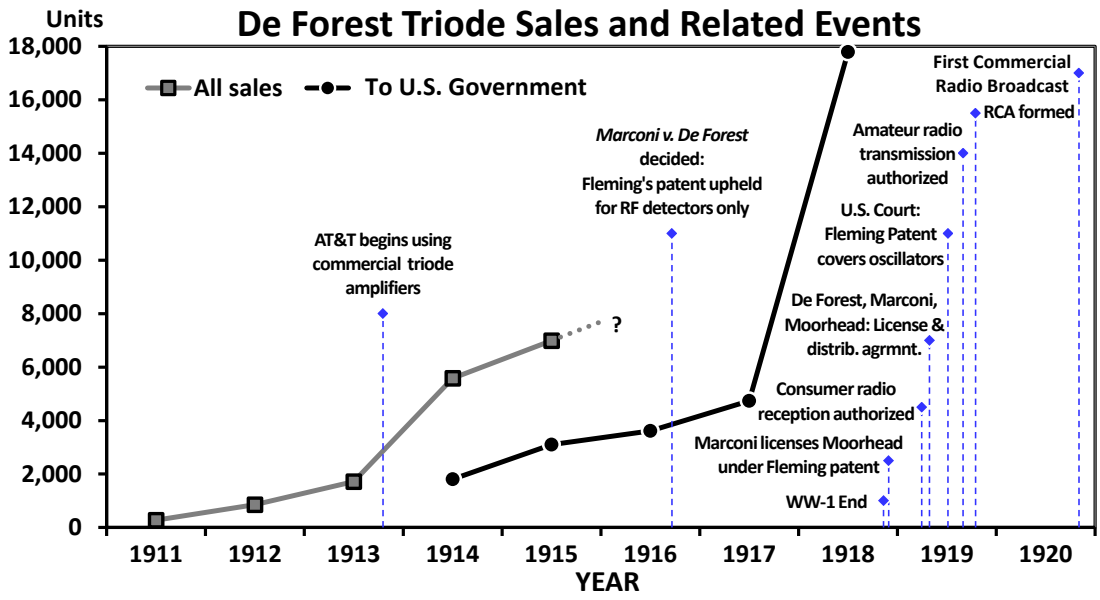

Figure 2. Sales of De Forest-manufactured Triodes and Related Events 1911-1918. *Sources*: 'All sales' from Tyne's figures for McCandless' (De Forest's contract manufacturer) supplies of triodes to De Forest (Tyne, 1977, p108-111, 131) (data for 1915 estimates the last quarter's sales by the average monthly sale of the first nine months); 'To US Government' is based on De Forest's sales to the US Government until February 1919, as reported in aggregate over multiple year blocks in (Tyne, 1977, p130-131) and estimated for each year by a proportional allocation for each triode type. Note – ? indicates no data for 'all sales' 1916

In Figure 2 we chart De Forest triode sales data from tables available in Tyne's monograph (Tyne, 1977, p110-111, p131) to more readily identify when the triode detector became commercially important. The upward inflection in De Forest's triode sales from 1913 is evident.[6] Other manufacturers of triodes have shipped much larger numbers of triodes during these years. As Table 1 shows, in 1918 alone, 700,000 triodes were sold to the U.S. government by the top four triode manufacturers. During the war the Moorhead company was producing 30,000 triodes per month for the Allied governments and in 1919 had a contract for supplying Marconi, acting as a distributor, for 50,000 triodes per month starting in July 1919 (Electrical World, 1919).

[6] This growth matches the market share growth of "Audions" (triodes) that Marriott reports in Item 5 in Chart 2 (Marriott, 1917, p182).

Triode sales to the U.S. Military	
	Units sold in 1918
Western Electric, Moorhead and De Forest	500,000
General Electric	200,000
Total	**700,000**

Table 1. 1918 triode sales to the U.S. government. *Source*: (Tyne 1977, p146).

It should be clear from Figure 2 and Table 1 that major developments in vacuum tube technology and radio circuits employing them had to have taken place well before these nearly million tubes were sold.

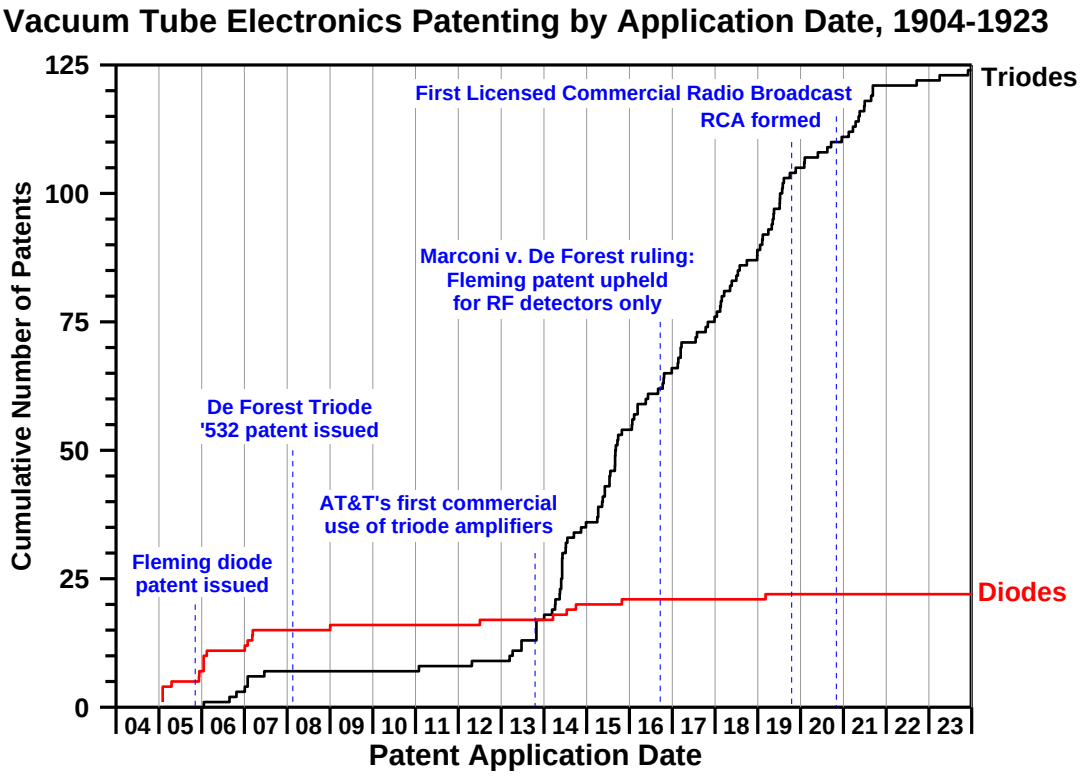

Figure 3. Key vacuum tube electronics and radio circuit patents by device type (diode-related or triode-related) and by application date. Source of patent data: the George H Clark Radioana Collection, Archives Center, National Museum of American History.[7]

[7] George H Clarke Radioana Collection, Archives Center, National Museum of American History, Series 52: "Receiving Vacuum Tubes, 1905-1949", Box 231 folder 3 and Box 232 folders 1-2 entitled "Vacuum tube patents" and sub-ordered through the folders by year ranges: see Smithsonian Clark Radioana Collection. It is clear from an amended and updated list by Clark (in Box 235) of the patents contained in two of these folders that Clark sought to build a list of significant vacuum tube patents in radio but the precise criteria for selection are not stated. Clark was an RCA executive who testified in court frequently on the basis of his expertise and collection (Smithsonian Clark Radioana Collection p5).

That development is exhibited by a sustained high rate of triode-tube patenting in Figure 3,[8] a plot of the cumulative patenting rate by application date of vacuum tube electronics and radio circuit patents. Figure 3 shows how triode development came to dominate the field of vacuum-tube development from 1912, well before any event alleged to have blocked development. This indicator of triode development continues without break or inflection through the 1916 and 1917 court decisions and we find it especially significant that Figure 3 shows a patent rate (intensity) *before* the formation of RCA in 1919 that is not lower than that *after* its formation—there is no evidence in Figure 3 to support the theory that triode developments were retarded.

Appendix lists another indicator of vigorous development prior to RCA's formation, the milestone triode-based inventions that created the *new fields* that later became known as *Electronics* and *Telecommunications*.[9] These include the inventions of negative grid biasing in 1912 and push-pull amplifiers in 1914, both for eliminating signal distortions, the high vacuum tube invention in 1913, the regenerative receiver in 1913, the use of heterodyning for improved radio frequency selectivity and sensitivity in 1919 and for use in metal detectors in 1920. It also included the invention of Single Sideband communications in 1915, used today in short-wave communications; several circuits that are known as staples in electronics such as the Hartley and Colpitts oscillators in 1915 and 1918 respectively; crystal oscillators in 1918, and binary "Flip-Flop" circuits in 1919, used in modern electronic computer memories. See (Thrower, 1986) for historical review of some of these advances pertaining to the development of AM radio.

The fact that the Fleming diode patent and the related patent litigation had no blocking

[8] Figure 3 is based on Clark's list of patents as of 1926 and we believe that the apparent reduced rate during 1922-1926 is a censoring artifact due to Clark not having collected patents filed earlier but not yet issued because of Patent Office pendency.

[9] The selection of milestone patents was by one of the authors, Ron D Katznelson, in his capacity as one skilled in the art of electronics and telecommunications engineering. The Appendix is his selection of the significant Clark-listed patents of Figure 3 and other inventions known to be significant in the field and found to have occurred in the pre-RCA period.

effects on the sale of triodes and the robust development of triode-related technologies can be seen in Figure 2 and Figure 3 respectively. The apparent delay in triode-related activity until after 1912 had nothing do with patent blocking (Marconi's diode patent suit against De Forest commenced only in 1915), as it took some time for De Forest and others to recognize the full potential of the triode, as the Appendix shows. According to Howeth, very little basic research was done prior to 1912:

> "Development in the United States was accomplished without very exact quantitative knowledge of the involved [technical] factors. … Most of the commercial radio interests in this country, with the exception of Fessenden, Stone, and a few others, were more interested in establishing communication networks or in financing stock promotion than in providing the necessary funds for research and development of more efficient apparatus" (Howeth 1963, p133-134)

It is reasonable to infer that Marconi's decision to assert the Fleming diode patent against De Forest only in 1915 is because triodes were becoming commercially significant at about this time. Indeed, the ten years that elapsed before assertion appear to be an example of how a patent is not necessarily asserted against a product believed to be infringing unless it is commercially worthwhile to do so. In preparation for patent assertion by Marconi, Fleming added a disclaimer to limit the scope of Claims 1-6 and 10-15 in November 1915. As originally issued, Claim 1 of Fleming's patent read:

> "The combination of a vacuous vessel, two conductors adjacent to but not touching each other in the vessel, means for heating one of the conductors, and a circuit outside the vessel connecting the two conductors."

This text can be read broadly to include the prior art and it did so by limiting the claims of the Fleming patent to "high frequency alternating electric currents or electric oscillations of the order employed in Hertzian wave transmission."[10] Hertzian waves were the contemporary word for radio waves so the disclaimer retrospectively limited the claims to a radio frequency (RF) detectors.

When the patent suit commenced, the district court accepted the late disclaimer and

[10] See disclaimer at the last page of U.S. Pat, No 803,684 to Fleming.

construed Fleming's claim as limited to radio frequency detection and observed that the Edison tube was prior art to the original Fleming claim. *Marconi*, 246 F. at 946. Edison had shown 20 years earlier that current from a heated cathode (thermionic electron emission) to a cold anode, both sealed in a vacuous vessel, exhibit the diode effect – current flows in one direction only. Such prior art was Edison's US Patent No. 307,031, which was also noted later by the Court of Claims *Marconi,* 81 Ct. Cl. at 732.

Fleming *did not* invent the vacuum tube diode—he invented its use for RF detection.[11] The Marconi Company would win its suit for infringement of the Fleming diode patent against De Forest's triode radio *detector* device in 1916 (*Marconi* 246 F. at 946), a ruling that was affirmed in 1917 (*Marconi* 243 F. 560).

3.2 Development of the revolutionary properties of the triode

It was alleged that the Marconi diode and De Forest triode patents "overlapped" such that "[n]either company could manufacture the triode" (Maclaurin, 1971, p85), causing "up to ten years of delay" without which perhaps "FM broadcasting … would have appeared sooner" (Merges, 1994, p85-87). If true, the fact that both the Fleming diode and the De Forest triode patents were *not* enforceable in Great Britain, should make radio developments in Great Britain an important "control."

The Marconi Company owned the Fleming diode patent in Great Britain (Patent No. 24,850) but it had never asserted it. Once the US legal situation had been settled in its favor, the Marconi Company attempted the same disclaimer to its British diode patent claims prior to an application to extend the term of that patent, perhaps with the view to assert it. As Morse explained, the Fleming British Patent "was bad, as its inventor had

[11] Years later, when the Marconi interests sued the US government for past infringement of devices made by contractors for the government, the US Supreme Court would hold that the 1916 district court had erred in accepting the late disclaimer and that the claim must be construed broadly as originally issued, rendering it invalid as anticipated by the Edison tube prior art. *Marconi Wireless Telegraph Co. of America v. US,* 320 US 1 (1943).

claimed too much. Its assignees sought to amend it by disclaimer when it was about to expire, but were unsuccessful" (Morse, 1943). The application for term extension was thus unsuccessful and the Marconi Company's diode patent expired in Britain in 1918 (Morse, 1925, p38). There was therefore no presumptively-enforceable, pioneer diode patent in Britain throughout the triode development period and the diode technology would be freely available in Great Britain. Further, De Forest's British patent on his triode (No. 1,427/08) was never asserted; it had lapsed in Britain in 1912 when he failed to pay the renewal fee, whereas the US counterpart would expire on February 1925 (Morse, 1925, p38). No pioneer patent rights and no patent thicket could have materially retarded vacuum tube development in Great Britain.

If US radio development had been retarded by difficulties in negotiating licenses for the Fleming diode or the De Forest triode patents, we should expect British development to have been ahead of the US. Of the many candidates for a commercial marker of relative "advance" in radio development with which to compare these two countries, we may take the dates for first continuous-sound broadcast to the general public in Great Britain and the US. Here we find the US nearly two years *ahead* of Great Britain: the first broadcasts to the general public occurred in the US in November, 1920 (Davis, 1928, p198) and in Britain in May, 1922 (West, 1972), which tells us that neither the diode patent nor the triode patent, licensed or not, retarded US radio development. We also know that FM radio was invented in the U.S. by Armstrong and not in Great Britain.

As a matter of logic, if the diode patent claims effectively covered the technology of the triode, it would not have been possible to sell licenses under the triode patents to develop the triode without a license from the owner of the diode patent. But after 1912 when the advantageous properties of the triode were widely recognized it *was* licensed for development, with a license from the Marconi Company perceived as unnecessary: AT&T bought from De Forest the exclusive rights to make and use the triode in telephony in 1913

for $50,000, then as they developed it and understood its potential, the radio rights in 1914 for $90,000 and finally in 1917 AT&T would pay $250,000 for outstanding rights to De Forest triode patents, including the pending feedback and regenerative detector patents crucial for the development of vacuum-tube broadcast receiver technology (Archer, 1938, p135).

There is evidence that the prospective legal outcome of an infringement suit was not deterrent: AT&T's legal department had assessed the risk that De Forest's product would be subject to infringement suit by the American Marconi Company at the time AT&T purchased radio rights to De Forest's patent in 1914: but the company proceeded anyway (Aitken, 1985, p247, Hijiya, 1992, p91). By 1915, AT&T had implemented the first transcontinental telephone lines with the aid of the improved triode acting as a line amplifier. So the revolutionary properties of the triode were in commercial use in the form of a telephone line amplifier before, during and *after* the 1916 and 1917 court decisions.

While such significant development occurred outside De Forest's company, in his license agreements with AT&T, De Forest had retained a personal, non-transferable or assignable right under his patent to manufacture triodes for sale direct to amateur radio users and to the US government – and the right to license the Marconi Company to use the triode (Tyne, 1977, p115). It is evident that the triode was being sold to, and used by, the US government, amateur radio users and AT&T in the periods up to and after the court decisions of 1916 and 1917; it is sales to these customers that are captured in Figure 2 and Table 1.

The US government also intervened directly in radio operations by Executive Order following the declaration of War in April 1917. President Wilson ordered the Navy Department to take over "such radio stations within the jurisdiction of the United States as are required by the Naval Communication" and "that all radio stations not necessary to the

Government of the United States for Naval Communications may be closed for radio communication and all radio apparatus therein may be removed therefrom" (Executive Order 2605A, 1917). By this order, the US Navy also controlled amateur radio reception and there was therefore no lawful civilian market in radio equipment during the War and therefore no patent infringement concerns. It is ironic, since this is an investigation into the role of patents in development, that it was a government-mandated closure of amateur radio stations that eliminated the major civil market for De Forest's triode detector, the market that supported the growth of his business until the War (Carneal, 1930, p273).

The significance of these interventions for our inquiry is that except for the liability incurred by the government (accounted for many years later), existing patents were irrelevant for development during the War, while technology diffusion and development proceeded apace. The War saw the US Navy set and meet ambitious development targets for the supply of vacuum tubes, establishing long production runs and component standardization (Howeth, 1963). The corporate R&D laboratories of AT&T (Western Electric) and General Electric were important contributors and Tyne recounts multiple avenues of research into the tube's functions which radically altered it from the primitive, erratic craft product with short life span made for De Forest by his manufacturer McCandless, into a reliable component for advanced applications (Tyne, 1977, p86-88).

Many firms had exploited their freedom to use patented technology for supply to the government before and during the War (Howeth, 1963, p374) and at its end in November 1918 they were left in possession of much state-of-the-art radio technology that would again be potentially subject to infringement suits by the relevant patents *should they now supply civil markets*. This unique situation might be considered a "natural experiment" on the business conduct of firms that find themselves in a patent "thicket" or "anticommons": would there be an explosion of infringement suits; bilateral licensing negotiations with

divergent expectations of the parties resulting in consummation of none; or would there prove to be several routs for successfully-bargained licenses?

Figure 2, Figure 3 and Table 1 above confirm that the triode was in uninterrupted development before, during and after the Marconi suit and before and well after the end of the War. This contradicts the widespread interpretation of the 1916 court decision referred to in the introduction. We consider two legal events that enabled this uninterrupted development; first, the 1910 Act providing immunity from infringement liability for suppliers of patented products to the government and second, the narrow scope of the 1916 decision in *Marconi*, 246 F. at 942.

3.3 The legal background to radio development and the 1916 decision

Congress passed the June 25, 1910 Act enabling patentees to sue the government in the Court of Claims for just compensation when the government used infringing products ordered from contractors.[12] By 1914 the prevailing case law including the *Crozier* Supreme Court decision in 1912 construed the 1910 Act as precluding patentees from having any patent infringement cause of action against equipment suppliers to the government and held that only the *government* could be sued to recover lost royalties, although it could not be enjoined from procuring and using infringing products.[13] Owing to this law, there had been many, including numerous new manufacturers who had, at the government's request, supplied infringing products to the government with effective immunity from infringement

[12] Public Law 61-305, Ch. 423, 36 Stat. 851, (June 25, 1910).

[13] *Crozier v. Fried. Krupp Aktiengesellschaft,* 224 U.S. 290, 301 (1912) (Ruling the district court's dismissal as proper and instructing the plaintiff to file a complaint *directly* against the U.S. government in the Court of Claims to recover infringement damages); See also *Marconi Wireless Telegraph Co. of America v. Simon* 227 F. 906 (S.D.N.Y. 1915), *aff'd*, 231 F. 1021 (2d.Cir. 1916), *rev'd*, 246 U.S. 46 (1918); *International Curtis Marine Turbine Co v. William Cramp & Sons Ship & Engine Bldg Co.* 232 F. 166 (D.C.Pa. 1916) (Under Act June 25, 1910, authorizing the United States to appropriate a license to use any patented invention, a contractor, who makes a patented device for use of the government, is not liable for infringement), *rev'd*, 246 U.S. 28 (1918).

suits (Howeth 1963, p374). This state of the law remained until March 1918.[14] Until then, federal district courts *would dismiss any patentee's suit against radio equipment manufacturers*, directing the patentee to file instead suit against the U.S. government in the Court of Claims to recover any infringement damages (*Crozier*, 224 U.S. 301). Moreover, because the government could not be enjoined from procuring infringing products (*Crozier*, 224 U.S. 308), no radio supplier to the government was ever at risk of having their radio sales halted on account of patent rights. The Fleming diode patent could not have blocked production of the triode by any supplier to the government and as shown in Figure 2 and Table 1, the government was a source of demand for triodes that was far greater than the pre-War civilian markets for radio.

It is clear that the 1916 Marconi infringement suit against De Forest concerned "Defendants' alleged infringing device… the so-called P.N. Type Audion De Forest *Detector* [emphasis added]" (Marconi, 246 F. at 952). In other words, it concerned De Forest's implementation and sale of the triode as a *radio detector* product. The court did not accept defendant arguments that the De Forest detector had a different mode of operation to the

[14] Despite changes in the law in March 1918, in practice government suppliers were never deterred by the threat of infringement suits. On 4 March 1918, the Supreme Court decided two cases, *Cramp v. Int'l Curtis Marine Turbine Co.*, 246 U.S. 28 (1918) and *Marconi v. Simon*, 246 U.S. 46 (1918), that reversed the decisions previously rendered by the lower courts and held that patentee's right to recover damages from the U.S. government does not absolve a directly-infringing manufacturer from liability. *Only then* did the government find itself confronted by manufacturers' threats to cease production unless the government provided indemnity, which it promptly did by way of specific indemnification letters sent to its suppliers. For example, Acting Secretary of the US Navy Franklin D. Roosevelt wrote on May 2, 1918 to Sperry Gyroscope Co. "In order that you may be protected against litigation for any purpose by reason of alleged infringement of patents the Department hereby guarantees to hold and save you harmless from and against any and all suits of which you shall give it immediate notice that may be brought against you for or on account of any alleged infringement of patents." George H. Clark Radioana Collection, Series 120, Litigation in Radio/box 321/folder 5. In parallel, Acting Secretary Franklin D. Roosevelt wrote to the Marconi Co. on May 7, 1918, overriding its objections to an earlier request, that the US Navy Department "directs and requires that you immediately take the necessary steps to procure from the courts having jurisdiction orders suspending the proceedings in the above mentioned cases [Emil J Simon and K&C Co.] during the continuance of the war" George H. Clark Radioana Collection, Series 120, Litigation in Radio/box 321/folder 6A. Congress, by an act of July 1, 1918 (Ch. 114, 40 Stat. 705), reiterated the intentions contained in the Act of 1910, amended it and codified in statute the government indemnification given to suppliers. See (Howeth 1963, 373-375).

Fleming patent detector; it understood the triode to function *as* a Fleming two-electrode detector and so it found in favor of Marconi,

> "…the physical ocular fact is that in the alleged infringing P.N device, the Fleming detector… is used, and the broad claim No. 1 of the Fleming patent is infringed… Claims 1 and 37 of plaintiff's patent are valid and infringed by defendant company; defendants' counter-claim will be dismissed" (*Marconi*, 246 F. at 955).

This decision had *nothing to do with De Forest's exclusivity for the amplification property of the triode* – this is made especially evident in the supportive text of the 1916 decision; "At the opening of the trial plaintiff confessed judgment as to claims 4 and 6… [of U.S. patent No.,] 841,387… and claims in issue of… [U.S. patent No.,) 879,532" (*Marconi*, 246 F. at 942). These claims described in patent 879,532 a 'device for amplifying electric currents' and in 841,387 an 'oscillation detector' so the Marconi Company admitted infringement of claims concerning the *amplification* and *oscillation* properties of De Forest's triode invention. Since this distinct and separate matter of infringement was not disputed, it is only referred to again when it is stated that De Forest was entitled to compensation from the Marconi Co. (Marconi, 246 F. at 955).

In sum, the 1916 decision upheld the Fleming patent under a narrow claim construction limited to RF detection but not for amplification, oscillation or for any of the other revolutionary properties of the triode. At best, the Marconi Co.'s claims could only cover the detector implementation of De Forest's triode, one of continuing marginal commercial importance, as described in section 3.1 and stated to be such by the De Forest Company: "The Audion [triode] Amplifier and the Oscillion, generator of undamped oscillations for transmitter purposes are unaffected by the recent [1916] litigation. These devices now constitute the largest part of the De Forest Company's business."[15]

Evidently the FTC, Maclaurin and other historians quoted in section 2 were mistaken in

[15] De Forest Radio and Telephone Co. public letter (undated) 'The Audion – Fleming Valve Litigation", in George H. Clark Radioana Collection, Series 120, Litigation in Radio/box 321/folder 3.

their interpretation of the 1916 decision. The error has not been pointed out before but it matters because it has unintentionally helped mislead analysis of the decision and encouraged unwarranted inferences to be fed back into patent law policy scholarship.[16] Given its importance we suggest that its origin is in an oversimplified rendering of the two infringement findings within the 1916 decision; we recall that Maclaurin wrote,

> 'The court decided that De Forest had infringed the two-element Fleming vacuum tube, while Marconi had infringed the three-element De Forest patent. Neither company could manufacture the triode' (Maclaurin, 1971, p85)

This rendering exhibits fundamental misapprehension of the patent system; first, it was not 'De Forest' that infringed, but the '*De Forest detector'* device that was found to infringe – but it was not found to infringe another device as stated by Maclaurin ('the two element Fleming vacuum tube') but to infringe specific claims (No.s 1 and 37) of the Fleming *patent*. Second, Marconi admitted infringement, but not of 'the' 'three-element De Forest patent' but of specific *claims* for amplification and oscillation properties of the triode in two of De Forest's patents, 841,387 and 879,532. Maclaurin's deduction 'Neither company could manufacture the triode' simply does not follow once the factual detail of the infringement findings are restored; De Forest was free to continue to license and manufacture the triode for any purpose other than as a radio detector; both companies were free to cross-license each other in the future; a court decision per se cannot 'block' manufacture.

Nevertheless, given that the erroneous interpretation of the 1916 decision is so entrenched, we note that it did result in the grant of an injunction, but with the condition that,

> "If an appeal from interlocutory decree is to be taken the injunction will be suspended provided defendant company (a) gives a bond in a reasonable amount; (b) makes monthly

[16] There is insufficient space here to document fully how this mistake by the FTC and Maclaurin has influenced later scholarship; but the influence is wider than the histories cited here: eg. Sabety argues nanotechnology patents today resemble the situation in radio patents described by Maclaurin and allegedly holding back radio development: therefore Sabety advocates a government-imposed non-exclusive licensing policy for foundational patents generated by publicly funded nanotechnology research today (Sabety, 2005).

reports as to sales, and (c) is expeditious in appealing."[17]

De Forest did so appeal, so it was when the 1916 decree was affirmed by the appellate court in May 1917 that the suspended injunction was in principle rendered enforceable - but in April 1917 the US had entered the First World War (WW1) and the legal context for radio development had entirely changed. The civil market was suspended and government became the only significant customer for triodes and as described above, the prevailing law pertaining to infringement suits against suppliers to the government protected De Forest and any other manufacturers for the government from infringement liability. Only with the Post-War resumption of civil markets for radio could the Marconi Company possibly have enforced the diode patent - and then only on De Forest's triode implemented as a *radio detector product*.

3.4 Post-War Resumption of Civil Radio Markets

We note that the US Navy relinquished control of radio stations in stages to private operators but did so much later than the end of the War in November 1918. The reason was that Secretary of the Navy, Josephus Daniels, was engaged in an (ultimately futile) attempt to have Congress pass a law granting the Navy permanent ownership of radio assets and was reluctant to return these assets to private hands (Archer, 1938, p174).

3.4.1 Marconi Company Licensing of the Diode Patent

The amateur radio markets upon which De Forest had depended prior to the US entry into the War were reauthorized by the US Navy in April 1919 and in September 1919 when amateur transmission under license was allowed (Douglas, 1987, p298). The earliest date at which the Marconi Company might choose to enjoin De Forest's company would therefore be after April 1919. This never happened because immediately after the War on November

[17] The 1917 decision refers to the existence of an injunction, but the Westlaw version of the 1916 decision does not contain the addendum which describes the conditions of the injunction granted in September 1916. The addendum can be found attached to a copy of the trial notes in an appendix to Fleming's book '*The Thermionic Valve*' (Fleming, 1919, p267).

30, 1918 the Marconi Company granted a nonexclusive license to Moorhead Laboratories "to make and sell equipment under the Fleming patent to radio amateurs and to any government" (Tyne, 1977, p171). Moorhead Laboratories was the most successful of the new entrants, non-liable for infringement Wartime manufacturers of triodes with production during the War for the Allied governments reaching 30,000 per month (Electrical World, 1919, p1349). In consideration for the diode patent license, Moorhead stipulated infringement of the diode patent, paid damages and agreed to pay future royalties to the Marconi Company (Tyne, 1977, p171-172). Moorhead now began negotiations with De Forest for a license to use the triode patents which resulted in an agreement signed on April 30, 1919 and intended to run to 1925, the agreement being that Moorhead would manufacture tubes for De Forest under his retained personal rights:

> "Then De Forest was to sell all such tubes to the Marconi Company, which agreed to act as distributing agent and sell tubes back to the De Forest Radio Telephone and Telegraph Company and to other purchasers. These tubes were to be sold to the public for amateur and experimental use in radio reception and amplification" (Tyne, 1977, p172).

So months before the Marconi Company was *able* to enjoin De Forest, it chose to negotiate a complex licensing agreement that exploited the manufacturing capacity of a third party to once again produce the triode deployed as an RF detector for amateur radio markets. This agreement was cancelled effective July 30, 1920, but De Forest and Moorhead continued manufacturing triode tubes through various arrangements and companies (Tyne, 1977, p175). The object of the Marconi Company appears clear enough: to establish a royalty income, and it did so through coordination with other right holders.

3.4.2 Pioneer patents pooled to create RCA

As civilian radio markets started to expand after the end of the War, manufacturers and patent right holders needed an alternative licensing regime to their unfettered war-time access to patented technology. The formation of RCA achieved this purpose by the pooling

and cross-licensing of independently-owned patents. This licensing arrangement *was* achieved in short order by private interests and did *not* require the intervention of the US Navy. The US Navy did intervene, but it did so to *prevent* a certain licensing arrangement: when the US Navy learned that General Electric (GE) had resumed its pre-War negotiations to sell its Alexanderson Alternator patent rights to the British-owned Marconi Co. in late February 1919, it persuaded GE to break off negotiations (Aitken, 1985, p323, Archer, 1938, p160-165); it feared that this technology would help consolidate the British company's monopoly in world communications; the Navy's motivation was to keep the technology in American hands and *not* to resolve patent "logjams" (Howeth, 1963, p353-358). The consequence was that GE created RCA as an alternative licensing arrangement.

The first action that GE took met the US Navy's concern that the technology be kept in US hands: GE and the American Marconi Company persuaded the British Marconi Company to sell its shareholding in the American Marconi Company to GE in September 1919 (Archer, 1938, p178). The Radio Corporation of America was granted a charter in October 1919 and by November 1919 GE had arranged for the American Marconi Company and RCA to be officially merged to create an American-owned radio operating company (Archer, 1938, p180). A patent cross-licensing agreement of November 1919 allowed RCA access to current GE patents including the Fleming diode patent and rights in exchange for GE's access to current and future RCA patents and rights.

The most important of the pioneer patents to be included were the rights to the triode patent that De Forest had licensed to AT&T, and AT&T's subsequent patents on triode developments. GE secured the agreement of AT&T to join the RCA cross-licensing arrangement only on July 1, 1920 (Aitken, 1985, p445) *after* RCA had begun commercial transmissions that were reauthorized by the US Navy on March 1, 1920 (Archer, 1938, p188). Aitken writes that these companies had signed a provisional agreement to create a jointly-owned radio company with exclusive rights to all vacuum tube patents as early as

May 29, 1918 (Aitken, 1985, p434). This suggests that these companies would have arranged some kind of cross-licensing deal on vacuum tube technology patents, even without RCA.

While the 1916 court decision has been widely and incorrectly attributed with giving the Fleming diode patent blocking power over the use of the triode, an unremarked July 1919 court decision *did find* De Forest's "Oscillion" to infringe the Fleming diode patent and so *did give* the diode patent that theoretical "blocking power" over the important oscillation property of the triode, a property fundamental to the subsequent development of radio transmission and reception (*Marconi Co., v. De Forest Radio Telephone and Telegraph Co*, 261 F. 393 (SDNY 1919). However, neither AT&T nor GE had yet achieved development of the power vacuum tubes to the point where it could substitute for the Alexanderson alternator as a superior transmitter technology. GE would first develop prototype transmission equipment based upon its 20 kW Pliotron vacuum tubes in 1922 (Brittain, 1992, p176-177). The 1919 decision presumably served only to increase the strength of GE's negotiating position as it sought to bring AT&T and its advanced triode technology into the RCA cross-licensing agreement.

Finally, Westinghouse pre-empted RCA in acquiring the heterodyne patents and an option on Armstrong's superheterodyne circuit patent, issued to Armstrong in June 1920 (Aitken, 1985, p467-468).[18] As cooperative licensing arrangements benefitted all parties, RCA acquired the necessary licenses to this fundamental receiving circuit technology in exchange for the admission of Westinghouse to the GE-RCA-AT&T patent cross-licensing agreement in 1921 (Aitken, 1985, p478-479). That established RCA as a holder of a wide range of patent rights for radio.

[18] The superheterodyne receiver achieves orders of magnitude improvement in frequency selectivity and sensitivity owing to its frequency down-conversion to *low* and *fixed* intermediate frequency (IF) narrow filter/amplifier prior to detection. It would prove basic to all future receiving technology in the broadcast-to-home radio development (Armstrong, 1924, Thrower, 1986).

4. Discussion - Alleged Empirical cases of Holdup

As explained in Section 2, economic "holdup" was attributed to the alleged patent thicket. In economics, holdup has long been conceived as the possibility of post-contract opportunistic behavior (Coase, 2006, p259, Klein et al., 1978, Williamson, 1985): once a supplier has made post-contract, significant investments in buyer-specific assets, ("sunk costs") there is a theoretical risk that the buyer will attempt to extract more favorable terms through threat of withdrawal. Yet these authors emphasize that economic agents are aware of this possibility and so take actions to forestall its occurrence (Klein, Crawford and Alchian, 1978, p298, Williamson, 1985, p114).[19] Since this theoretical work draws on Coase (Coase, 1937) it is noteworthy that Coase always remained skeptical about the importance of holdup as an empirical phenomenon.[20] Yet following the work of Klein, Crawford et al. (1978) and Williamson (1985) the General Motors (GM) – Fisher Body case became developed in economics as the "classic" empirical case of actual holdup and market failure (Casadesus-Masanell and Spulber, 2000, p67) – until subsequent thorough empirical investigation proved this interpretation to be erroneous (Casadesus-Masanell and Spulber, 2000, Coase, 2006). The case illustrates the need for thorough empirical testing of holdup theories (Coase, 2006, p277).

One might therefore expect that economic agents in the patent thicket would be aware of and would take steps to forestall the realization of holdup and potential economic loss in

[19] Today, for example, vertical integration that forestalls the possibility of holdup is said to be illustrated well by the banana industry (Galetovic et al., 2015, Kieff and Layne-Farrar, 2013); see the classic account of the coordination problems of banana production and distribution (May and Plaza, 1958). Another recognized tactic to forestall holdup are long term contracts; these have been found typical for supply of coal to coal-fired generator plant (Joskow, 1987, Joskow and Rose, 1985).

[20] So Coase found that if assets are required solely for one customer, the cost is typically incurred by that customer so the problem of opportunism is entirely avoided (Coase, 2006, p259). Coase' observation based on his empirical work that long term contracts were typically incomplete convinced him that opportunism was not a serious or common problem (Coase, 2006, p260) and in general he concluded that opportunistic behavior is deterred by the need for future business.

development. Whether this is so and whether development block[21] actually occurred in these industries should be apparent in inflections in the many empirical indicators of development which we take to include; patent count rate, rate of product price changes, investment rate, rate of expenditure on research and development (R&D), new product releases and specification of the detail of actual cases of holdup. This kind of evidence has been compiled to refute the theoretical argument that holdup and development block is likely to occur in the biotechnology and software industries (Barnett, 2014, Buckley, 2007, Mann, 2004) and in general, the patent-intensive industries experience steep and continuing product price declines of much greater magnitude than the low-patent intensive industries (Galetovic, Haber and Levine, 2015).

There are specific patent cases widely believed to illustrate actual holdup and development block. As in the Fisher Body – GM case, thorough empirical analysis has refuted such beliefs in the early U.S. aviation industry (Katznelson and Howells, 2015), in the early U.S. incandescent lamp industry (Katznelson and Howells, 2014) and in the "first American Patent Thicket" in the early US sewing machine industry (Mossoff, 2011). As former Chief Judge Randall Rader has pointed out, the idea that actual holdup occurs asks us to believe that the patent law, designed to promote innovation, actually "works against itself" and he remains highly-skeptical that this is so given the lack of robust empirical support for such beliefs.[22]

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21 'Block' and 'holdup' have the essential same meaning in this paper, a delay in the process of development caused by patents.

22 *See* (Rader, 2013, p4) "Academics often charge the Patent system with creating a so-called "tragedy of the anti-commons." This academic canard suggests that a "thicket" of patents can actually inhibit innovation; that the administrative burdens of enforcing patents can multiply to frustrate the goal of the Act. Thus, the law of innovation supposedly works against itself. In an age of empirical research to verify every legal hypothesis, I would urge you and any policymaker to reject this academic supposition – whether it comes from a high court or any other source – until and unless it is verified by empirical data. By the way, the only studies on this topic that I have seen could not verify this guess but generally confirmed the opposite – that patents spur innovation."

5. Conclusion

We have shown that a robust development of the triode technology coexisted with the enforcement of more narrowly-defined rights than were previously understood under Fleming's diode patent. The widespread idea that the 1916 court decision generated a holdup in development of radio can be seen in retrospect to rely on an erroneous characterization of the 1916 decision by the 1924 FTC report and a vague and hence misleading rendering of the 1916 decision by the historian Maclaurin (see quotes in introduction). In fact, court decisions on the validity and scope of the diode patent altered the scope several times; although *who* controlled *what* changed, development continued under licensing arrangements adapted to the pattern of ownership rights.

We suggest that at the end of the First World War and given the widespread 'free diffusion' of radio technology promoted by freedom from infringement liability for government suppliers, the prospective transition back to civil markets and infringement liability might be considered a "natural experiment" in firms' conduct when faced with an extreme example of the "patent thicket" wherein more than one party holds pioneer patent rights. The result is consistent with economic theory and previous studies that find that the private sector adapts to avoid the realization of harmful consequences from prospective holdup; the private sector led the creation of a cross-licensing arrangement centered on RCA and so both established a legal framework for continued radio development and an accommodation of the US Navy's stipulation that there should be a US national radio company. A more positive rendering of this outcome is that it is consistent with the view that when the cooperative surplus from continued development is expected to be greater than under noncooperation, legal and organizational arrangements will be found to evade any prospective blocks and hindrances to that development.

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Appendix - Key vacuum tube-based electronics and radio patents

Application Date	Patent Number	Title	Assignee on Issue date	Inventor	Key advance in electronics and radio
April 19, 1905	803684	Instrument for converting alternating electric currents into continuous currents.	Marconi Wireless Telegraph Co.	Fleming, John A.	**Vacuum tube detector**
October 25, 1906	841387	Device for amplifying feeble electrical currents..	De Forest Radio Telephone Co.	De Forest, Lee	**Amplifier**
January 29, 1907	879532	Space telegraphy.	De Forest Radio Telephone Co.	De Forest, Lee	First use of **control grid** between cathode and anode
April 26, 1912	1231764	Telephone-relay.		Lowenstein, Fritz	**Negative grid bias** to eliminate grid currents that cause input circuit distortion
October 16, 1913	1558436	Electrical discharge apparatus and process of preparing and using the same	General Electric Co	Langmuir, Irving	**Gas-free, high vacuum,** relies solely on thermionic electron currents; facilitates repeatable and stable tube characteristics
October 29, 1913	1113149	Wireless receiving system.		Armstrong, Edwin H	**Regenerative detector**; provides orders of magnitude increase in receiver sensitivity
January 3, 1914	1128292	Electric-wave amplifier.	Western Electric Co	Colpitts, Edwin H.	**Push-pull** audio amplifier; eliminates all even-order distortions
March 20, 1914	1507017	Wireless telegraph and telephone system	De Forest Radio Telephone and Telegraph Co.	De Forest, Lee	**Oscillator**; recognition that a triode can be used in transmitters.
May 18, 1914	1137384	System for the transmission of intelligence.	Western Electric Co	Colpitts, Edwin H.	**Amplitude modulated RF oscillators**; combining modulation within the oscillator function
July 6, 1914	1130043	Alternating-current-responsive apparatus.	Western Electric Co	Van Der Bijl, Hendrik .J.	**Frequency-doubler** by dual deflecting grids
July 20, 1914	1219961	Means for indicating electrical characteristics of alternating currents.	General Electric Co	Langmuir, Irving	Grid used in CRT **oscilloscope** display; enables live waveform display in the lab
May 19, 1915	1210678	Thermionic amplifier.	Western Electric Co	Nicolson, Alexander M.	**Unipotential cathode;** cathode heated indirectly by separately-powered filament; isolation of triode operation from filament disturbances
June 1, 1915	1356763	Oscillation-generator	Western Electric Co	Hartley, Ralph L.V.	The basic **Hartley oscillator**
June 5, 1915	1195632	Circuit connection of electron discharge apparatus	General Electric Co	White, William C.	Filaments with **center-tap AC powering**; removing AC hum noise
September 3, 1915	1504537	Power-limiting amplifying device	Western Electric Co	Arnold, Harold D.F.	Signal envelope **limiter**; later used in FM

Application Date	Patent Number	Title	Assignee on Issue date	Inventor	Key advance in electronics and radio
September 7, 1915	1232919	Thermionic voltmeter.	Western Electric Co	Heising, Raymond A.	Vacuum Tube Voltmeter (**VTVM**); prevents loading the measured circuit
December 1, 1915	1449382	Method and means for signaling with high frequency waves	AT&T	Carson, John R	**Single-Sideband (SSB)** communications; uses half the bandwidth of AM; improved transmission power efficiency
March 11, 1916	1258548	Radiotelephony.	Western Electric Co	Englund, Carl R	**DSB suppressed carrier** communications; improved transmission power efficiency
September 5, 1916	1343306	Duplex translating circuits	AT&T	Carson, John R.	**Double-balanced mixers** for suppressed carrier communications
December 28, 1916	1325879	Vacuum-tube circuits.	Western Electric Co	Nichols, Harold W.	Parasitic **electrode capacitance compensation** by external inductor; facilitates very high frequency operation
February 17, 1917	1424866	Method and means for relaying modulated carrier waves	Western Electric Co	Wold, Peter I.	Distinct frequency **RF repeater** (using second harmonic); relaxes repeater's input-output isolation requirements
February 1, 1918	1624537	Oscillation generator	Western Electric Co	Colpitts, Edwin H.	The basic **Colpitts oscillator**
April 10, 1918	2212845	Generating and transmitting electric currents		Nicholson, Alexander M.	**Crystal oscillator**; orders of magnitude improvement in frequency stability over LC oscillators.
June 21, 1918	GB148582	Improvements in ionic relays		Eccles William H. & Jordan ,Frank W.	Triode-based **Flip-Flop** - a circuit that became the basis of electronic binary representation in computer memory
February 8, 1919	1342885	Method of receiving high-frequency oscillations		Armstrong, Edwin H.	**Superheterodyne receiver**; facilitates high frequency selectivity and improved receiver sensitivity
July 11, 1919	1403566	Vacuum-tube repeater circuits	Western Electric Co	Read, Harry S	Triode used as **active load** resistance; substantial improvements in linearity
May 28, 1920	1437240	Apparatus for detecting minute values of energy		Hanson, Earl C. & Carlson, Wendell L.	heterodyning two oscillators to detect low level signals; precursor of **metal detectors**
June 27, 1921	1424065	Signaling system		Armstrong, Edwin H.	**Super-regenerative** receiver; an additional oscillating circuit, produces a "capture effect" for improved interference rejection