So this is Convergence?

Technical, Economic, Legal, Cryptographic, and Philosophical Considerations for Secure Implementations of Digital Watermarking

by

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BLUE SPIKE

Didya Use Protection

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Forward

With the advent of digital technology to record analog signals and the new distribution methods it has propagated, the notion of the lone artist or inventor laboring in obscurity is fast becoming a thing of the past. It is now possible for a single creator of a work of music, video, or visual art (as well as many other types of creative endeavor such as fiction, computer code or product specs) to act as his or her own publisher, agent and distributor, bridging the gap between creator and consumer— a phenomenon that has been termed "convergence".

The potential freedoms offered to a self-sufficient provider of creative work by means of digital technology are considerable. At the same time, the distribution of various types of digitized media by record labels, motion picture studios and the like, by way of the internet, compact disc, or other means, already constitutes significant aspect of their respective businesses.

However, the convenience of digital technology for recording and distributing creative work has also given rise to unauthorized duplication of the digitized media, and more importantly unauthorized commercial resale, known commonly as "piracy". Concern over this type of activity has led inevitably to the development and implementation of digital watermarks. Based on the historical notion of watermarks, which used seals or images embedded in special paper

to protect official documents, digital watermarking hides information within the signal to identify the ownership or origin of a given piece of creative work.

A number of factors play into how digital watermarks can benefit those who profit from the sale of copyrighted material. By establishing the market value of a particular work, the cost benefit of digitally watermarking it may be determined. Digital watermark technologies come in several varieties, and some are indeed more effective than others at dissuading would-be media pirates.

Whether or not one decides to market digitally recorded media for profit, establishing a record that identifies a work's creator or owner has important ramifications. Those content creators or owners who chose to distribute their work "freely", i.e., there is no commercial transaction, do not make the same cost-benefit analysis regarding piracy but can still benefit from identifying their works at some later date.

Since digital watermarking is designed as a means of copyright protection, or as a substitute thereof, we consider in this paper how the law in the United States has kept up with technological advances and the parameters provided by this safeguard.

Digital watermarking is, in essence, a form of steganography (the art of concealing messages) and is less complex than the issues surrounding proper implementation of the technology. Insuring the permanence of cryptographic data through several rerecordings is but one of the concerns facing the fledgling

digital watermarking industry. Cryptographic security is what separates better digital watermarking technology from others.

Given the quickly changing scope of media currently being produced or distributed in a digital environment, it is difficult circumscribe all that may benefit from digital watermarking. Therefore, some philosophical consideration is given to the qualities that impart "value" to particular work of art. In the end, the desire to identify and protect valued creative efforts provides ample motivation to create technologies such as digital watermarking.

Each section of this paper deals with various aspects relating to the various Considerations for Secure Implementation of Digital Watermarking discussed above and may be read separately. An appendix dealing with Nyquist's theories on quantization provides information for those with interests of a technical nature. The additional background references listed at the conclusion of this paper direct the reader to further material on the subject.

Hopefully, there will be enough interest to expand this volume into a book, with pictures and further discussion on the selected topics. For those interested in our work, please visit us on the World Wide Web at **http://www.bluespike.com/.** I look forward to further discussions, which arise from this work.

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Technical, Economic, Legal, Cryptographic, and Philosophical Considerations for Secure Implementations of Digital Watermarking

At the convergence point between the creation of media works and its commercial distribution to consumers, digital signal processing (DSP) has provided us with an efficient means to approximate and distribute analog signals such as pictures, music, and video.

Digital watermarks, a form of steganography, is less complex than the issues surrounding proper implementation of the technology for security purposes. The security sought relates particularly to unauthorized duplication of the digitized media, but more importantly unauthorized commercial resale, known commonly as "piracy".

A number of factors play into how digital watermarks can benefit those who profit from the sale of copyrighted material. We concern ourselves in this paper with mechanisms of market behavior and related age-old legal issues. Those content owners who chose to distribute their work "freely", i.e., there is no commercial transaction, do not make the same cost benefit analysis of piracy but can still benefit from identifying their works at some later date. Additional relevant topics include cryptographic security and some speculation on the nature of media content.

Digital Sampling and Consumer Electronic Format Wars

Music, video, and still images are examples of copyrightable media, which may be digitally sampled. We define the sampling rate, or rate at which a signaling

process may be applied, in order to better describe approximations of the original analog signal. The process of sampling is based on theories proposed by Harry Nyquist, in the 1920's. The Nyquist Theorem posits that an analog frequency range (e.g., the highest of the frequency range) must be doubled in order to provide for a binary representation of the signal and allow for efficient processing as discrete values [1]. That is, since binary digital processes work with either ones or zeros, "doubling" the signal's highest frequency allows for digital sampling of the media signal.

The bounding limit for digitizing artistic works is how many frequencies are perceptually relevant to humans and differentiating between discrete binary representations and the continuous analog wave being manipulated. How much sampling is necessary is purely a function of time and cost restraints related to the subsequent playback. Ultimately, the decision is based on the approximated signal and its relationship to human auditory and visual perception. The two ingredients for any digitization system are digital filters and error correction. Because of the restraints of technology, digital filters can only approximate the analog wave, and the resultant error correction can never be perfect [1].

Media content may be considered essentially actual distributions of energy or matter; digitization is a process of making the continuous analog wave forms discrete samples "quantized in equal intervals of amplitude" [2]. Though digitization is not plainly evident when listening or viewing digitized content, the process is a matter of only temporarily rendering the signal as discrete values, zeros and ones, in order to be digitally processed. By reducing possible

degradation resulting from this process can never replace the fact that what we observe is *only* a representation of the original continuos waveforms [1, 2].

We use "spectral transforms" to sample the analog frequencies and reduce the computational demands of reproduction. Different transforms provide a number of related approximations but cannot replicate the analog signal perfectly. Whereas natural signals have components of noise, digital sampling introduces unrelated quantization effects that can also be described as noise. In effect, noise occurs naturally— acceptable levels of noise are subjectively defined. It is possible to describe perceptual models for any media signal where locations for data embedding can be invisibly or inaudibly achieved. Depending on the sampling rate, and related quantization effects, the higher resolution sought necessarily introduces larger data regions, or greater amounts of data, in the digitized carrier signal, in which to "hide" a digital watermark message.

Because of the widely inconsistent application of terminology, we define a "digital watermark" as being inherently different from traditional "watermarks" insofar as the embedded "watermark message" may also have *intrinsic value* independent of the media to be watermarked. All "digital watermark" embedding technologies are not equal; however, some hide information in the frequency range, others in the spatial range. Further, the choice of a whole data-set transform (e.g., the entire media signal) or a block-based transform (e.g., subsets of the entire data-set comprising the media signal) increases the variety of potential means for embedding information into a digitized media signal.

We believe the existence of attacks which exploit the weakness of choosing either frequency or spatial domains [3, 4] for images, forces watermarking technology to pursue more sophisticated implementations, namely that encoding is performed in both domains. Our own testing indicates survival against simultaneous cropping and scaling of the image, in essence, manipulations of both the spatial and frequency domains. At some level, the manipulations will result in a representation of the original copy distinguishable from the media prior to manipulation. As the media is further removed from the original expression, legal issues arise as to what would be considered the "actual original work". We discuss these later but raise the point to properly bound the limits of digital signal processing, in general, and digital watermarking, more specifically.

The most widely observable commercial digitized media is music, in the form of compact discs (CD). Focusing initially on audio will form a strong basis for relating digital watermarking to the complications inherent in security. We can observe that the human auditory system is capable of a perceptual range between 20 Hz and 22,050 Hz, where the psychoacoustic sensitivity is defined as sensitivity to a range of power of one billion to one and a range of frequencies of one thousand to one [5]. Acoustic artifacts can be detected in the range of one part in ten million, and audiophiles can typically focus their auditory senses to very fine signaling bands [5]. A real world example is the ability to hear a conversation in a noisy restaurant or bar. To ensure higher digital audio quality consideration is paid to effects in psychoacoustics. Namely, the human auditory system prefers noise to distortion creating a subjective inaudibility standard for digital signal processing and audio watermarking [1].

We believe attempts to encode in the amplitude phase alone, is far too periodic to escape perception by audiophiles [5, 6]. A parallel argument is that amplitude modulation in radio broadcast, such as AM radio, does not provide the quality inherent to frequency modulation, FM radio. Data encoding rates are also far below encoding rates achieved with perceptual codes working in both the frequency and time domains and do not meet audibility or practical implementation requirements for the audio industry [5 - 10].

What is clear is the human auditory system is capable of detecting noise at more discrete levels than the human visual system. Others better address these issues in related fields of research, but we disclose them to identify the bounding limits given the digital sampling of an analog signal. Applications for digital watermarking require a measure of sophistication to survive common, inadvertent manipulation of the watermarked content. Audio digital watermarking systems require approaches more closely linked to perceptual models of the music signal relating to the higher sensitivity of the human auditory system. Simply, perceptually-based "psychoacoustic masking" of arbitrary information, or digital watermarking of audio, is not difficult.

Compact disc

A compact disc has a defined specification of six sampling periods, 24 audio symbols with an additional nine bits (one bit for subcode, eight bits for parity). The 33 data symbols, comprising audio, parity, and subcode information, are multiplied by 17 channel bits. Finally, 27 synchronization bits are added for a total of 588 channel bits per single frame. More commonly we identify the

compact disc as having a 16-bit 44.1 kHz sampling rate. 128 samples are processed per frame, creating a starting point for processing digitized audio for the secure digital watermarking processes we envision.

The definition is less arbitrary than imagined but was chosen for computational efficiency, in order to define a consumer electronic device to be mass-marketed, as well as satisfying the demanding nature of audiophiles. Indeed, although many parties contributed to the development of digital audio over a period of years, Sony's error correction techniques and Philips' optical storage methods ultimately provided the basis for the compact disc. For every 128 bits, 96 bits is data, 32 bits are parity. Previous distribution of copyrighted music in analog format, a vinyl long-playing recording, and provided listeners with an easy means to compare two seemingly identical recordings. The LP, however, contained a physical representation of the actual analog music signal— the compact disc approximates the same signal in a manner arguably less dynamic.

A frequency of 44.1 kHz represents the doubling of the 22.05 kHz perceptually relevant to the human auditory system. Quantization effects are addressed by implementing Hamming error codes, and more specifically Cross-Interleave Reed Solomon, in an attempt to replicate the signal at higher error-free rates. Perfect error correction is computationally unfeasible [1]. Still, many audiophiles in such works as quiet classical pieces and those with strings observe noticeable quantization effects in compact disc recordings. Dither is suggested as a means to decorrelate quantization error, however, audiophiles would instead prefer higher sampling rates of 24 bits, even 32 bits, making floating point operations possible for more granular signal processing. 24 bits

96 kHz is currently being debated as the minimum sampling rate for DVD audio. Some recent announcements indicate more flexible approaches, including variable sampling rates and variable samples per window setting [13]. The area of DSP work is highly subjective, ultimately human perceptual models are the most appropriate measure in which to make design decisions [14]. Digital watermarking is related in the sense that lossy compression of a media signal is able to provide an encoder with the most perceptually relevant portions of the signal in which to embed watermark information. From a perceptual standpoint for actual watermark encoding some additional observations can be made.

We know that compact disc audio provides us with the following amount of data: 16 bit samples at 44,100 Hz, or cycles per second, a sampling rate, for a total 705,600 bits per channel. For stereo, a left and right channel, compact disc thus provides 1,411,200 bits of data per second. By modeling the encoder along the lines of perceptually-based compression algorithm, such as MPEG, we must ensure that the data to be hidden is not audible, nor is it easy to predict the locations. This model provides further for understanding just what is perceptually relevant; we do not believe it is necessary to watermark silence, although a silent passage has as much data as a passage with lots of perceptual relevance, in the song itself. In order to mathematically understand, from a digital signal processing standpoint, what actually is representative of the perceptually significant portions of the signal, we may break the music down into signalling bands, each representing a subset of the overall set of data comprising the recorded music.

We know signalling bands can be broken up in any number of ways and we also know that 0 Hz, representative of silence, and the Nyquist frequency, the

doubling of the highest frequency band we are able to perceive, double the 22.05 kHz band, resides in some cases in representations of frequencies we might not want to watermark, can be excluded. We will instead focus our encoding on the frequencies above 0 Hz and below 22.05 kHz. We do not have to always encode using this approach, but the watermarks are most likely to survive various manipulations and conversions if they reside in perceptually significant portions of the signal, what consumers are demanding, the music. If we chose not to encode in a perceptually-based approach, we must assume *the location of the watermarks will not be as secure as they could*; the defined watermarking region is divorced from the media it is supposed to identify and is more easily predicted [15].

However, if the decision to watermark is made, *to establish responsibility over copies*, we must encode in a manner which is able to survive common manipulations and conversions in both frequency and space, while being encoded at a level that does not affect the quality expected by artists and consumers of the media. Manipulations can be carried out in either the primary (frequency) or convolution (spatial/time) domains, or simultaneously in both domains, presenting higher hurdles to clear in surviving intentional or inadvertent erasure [3, 4]. Conversely, unscrupulous manipulations of the signal intend to preserve the perceptually relevant features of the signal, so that they retain commercial value, a direct descendant of the original untampered signal.

How we determine relevance for encoding requires that we have mathematical representations of amplitude, or physical sound pressure, "intensity" in acoustic terms. Where there are relatively low amplitude values, we can presume

watermarking will not effectively be hidden. Where there are relatively high amplitude values, again relative to the representation of the entire song, we can bound just what "locations" in the signal are candidates for embedding watermark information. Because others will have the same tools to figure out just what is perceptual in the signal, they will eventually make the same calculations, making our digital watermarking susceptible to erasure or overencoding using the same process [3, 4]. By taking a subset of the "candidate bits", both frequency values and those same values as they change over time, and having the watermark encoder randomize the actual embedding process, we force others to make more guesses as to just where the watermark bits are.

Watermarking is *necessarily* about commercial viability; periodic signals have little observable commercial value. Songs are unlike tones used for testing hearing; copyrighted music is generally not a single signalling band with the same characteristics over each instance of time. We do not concern ourselves with copyrights for tuning forks or individual notes on a piano. If our watermark is similar to a continuous tone in a greater set of signaling bands, we must be concerned with both audibility and easy detection or erasure. If the watermark bits are close to or interchangeable with the perceptually rich bits comprising the audible regions of the signal, wrong guesses, in essence "flipping" a bit from zero to one or from one to zero, degrade the quality of the recorded signal, since audible bits are being affected by this "randomization attack" [8, 9].

Ultimately, we seek to watermark at a level, which is below the noise inherently present in any analog media, further frustrating attempts at successful, inaudible removal. Pirates must pay a price in the form of unsalable, unauthorized copies

of the material. Fortunately, the information we encode need not significantly increase over time. A credit card number or invoice number, as represented in bits, will likely have, more or less, the same data size over a long period of time, relative to increases in the numbers of bits comprising a representation of an original analog media signal. As digitization allows us to represent analog media, such as pictures, music and video, at higher fidelity, more realistic representations result. At high enough fidelity, the approximations of the original signal become increasingly exact. In parallel, the total number of candidates bits for watermarking also increases. For instance, DVD audio with a sampling rate of 24 bits and 96 kHz yields us total data per second of: 24 x 96,000 = 2,304,000 bits per channel. With a left and right channel: 2 x 2,304,000 = 4,608,000 bits. With 5.1 channels, as is currently being considered, there is a further increase in available data, however, the channels will not all have the same data size. This figure gives us higher audio "quality" and many times the available data in which to encode watermark bits versus compact disc.

We describe digital sampling because the effort at introducing the compact disc was rife with many of the same complex issues surrounding electronic distribution of media today. A previous format war between *Matsushita* and *Sony*, VHS v. *Betamax*, was taxing on the consumer electronics companies who favored a more profitable resolution for the digital audio standard. More importantly, *Sony* and *Philips* possessed enough technology to propose a standard, which was acceptable to all consumer electronics companies. It also represented a comprise between the expense of the storage media, the optical storage inherent to compact disc, and a sampling rate sufficient enough to offer advantages over the media it was designed to replaced, the vinyl LP.

The market inevitably assisted in the pricing of the compact disc as it could not exceed retail pricing acceptable to consumers. Essentially, the pricing of albums was backended against the expense of optical storage cost, sampling rates and "bit depth", or the fidelity of the recording when played. The success of the format was able to profitably benefit these same companies, media companies and artists. Unlike a number of other competing formats such as *Betamax*, *Digital Compact Cassette* (DCC), and Digital Audio Tapes (DAT), compact disc was able to establish itself as a commercially-viable format, selling over 2.9 million players by 1985, the third year of introduction [16].

With more boxes, more music titles could be offered at lower, relative manufacturing cost. The result: a mass conversion of vinyl album collections to CD. The same may not be said if unfettered, perfect duplication of high quality, copyrighted works eliminates the ability to establish responsibility over copies. Ironically, this debate is not new; the introduction of the digital audio tape (DAT) focused less on a VHS v. *Betamax* format war than on the risks posed to creators and distributors of copyrighted music. *US Copyright Law, United States Code 17 Chapter 10* was enacted to provide for royalty payments from the sale of both DAT hardware and recordable DAT tapes and includes a copy prevention scheme called Serial Copyright Management System (SCMS), which comes under the *Audio Home Recording Act of 1992*, a law passed to protect copyrights [1, 17]. The weakness of SCMS relates directly to the fact that the security exists in header information about the audio file it precedes, not within the audio signal itself, as a digital watermark does [8, 9]. Beyond the scope of this paper, successful formats for commercially-viable media works provide a framework for media providers and manufacturers to stimulate

demand for consumer electronic products. But the order of success depends solely on a consumers' choice to purchase the new format. Analysis of market penetration can assist in determining the requisite investment in plant and equipment as well as distribution costs projected over years after introduction. Yet, because economies of scale in mass markets require "patient capital", commercial success is never guaranteed.

Compact discs cost less than cassettes to manufacture (?!)

It is not obvious that the manufacturing cost of compact discs is lower than cassettes, a separate carrier format, although wholesale and retail pricing for compact discs is higher [18]. Surely quality and durability of the format is a reasonable factor in such pricing disparity [19, 20, 21, 22]. But, the pricing discrepancy also reflects the strength of media companies in pricing carrier sales in an effort to recoup costs through control of the distribution of copyrighted works, not a purely market-based determination of the cost of goods sold in pricing [21, 22]. It also relates closely to arguments made by on-line retailers and others that the pricing of media should reflect underlying cost. Indeed, government agencies have investigated the issue on a number of occasions [17, 23]. However, corporations seek to maximize profits, with media, it is difficult to determine the payoff of a given media product in a highly competitive and speculatively-based industry.

Money trail Consumer electronics companies are able to sell more hardware. Computer companies seek demand for hardware, which is able to handle multimedia content, typically resulting in higher processor costs and more expensive computers.

Digital watermark requirements By design, digital signal processing is invertible, noninvertibility of the digital watermark message is invaluable. Simply, all digital signal processing is based on ensuring that what goes into a digital signal is relatively easy to get out, a strict linear relationship. Related to security, this has the unfortunate effect of ensuring that "unknown" signal locations are not "unknown" for very long.

Market Valuations of Creative Works Recognition and Piracy

Why do some artists receive greater monetary rewards than others do? Is a rich artist a better artist? Where is the convergence point between art and commerce? Can commercial success be predicted? Does the marketplace matter? What is recognition?

These questions strike at the heart of the commercial media business. While entirely subjective, the artist has benefited in many of the same ways consumers have with the advent of inexpensive digital signal processing. In the music business, which has been able to capitalize on the relatively low cost of compact disc manufacturing and playback devices, two forces evident in any media business have arisen. First, the number of available genres has greatly increased [21]. Second, the competition for consumer's time and money has spiraled upwards [19, 21, 22]. As with any investment decision, selling media products requires a time value of money analysis. The greatest factor of error in estimating the so-called "present value" of the ownership of a given media product is the ability to profitably sell the content at the lowest possible cost, inclusive of marketing and related promotion of the content to be sold, under highly speculative conditions. Competition for consumers' attention is usually less than predictable, further, outside of serendipitous discovery, the cost of promoting creative works is relatively time and cost-intensive. For these

reasons, entertainment companies, including music labels, behave similarly to venture capitalists: few investments pay off, the successes, however, can be very profitable.

What is highly misunderstood is the relevance of electronic commerce to the sale of media works such as still images, audio and video. It is safe to make observations about the impact of the World Wide Web on reaching potential consumers, but far less clear is any current analysis that digital distribution is a less expensive means to reach consumers versus physical carrier distribution. Contrary to many early portrayals of the Internet, those with more resources are able to market to audiences at an advantage to those lacking similar resources. Deeper pockets can pay for web site advertising or links to popular sites. It does not mean that only those with resources can succeed, any more than differentiations between the success of seemingly similar restaurants. Nor does it change the ability of large companies to actively seek exposure of their media, as they do in promotions at radio stations and music video broadcasts. The Internet has reduced the barrier to entry for those interested in seeking a potentially large audience; but, it does not necessarily reduce the cost of successfully selling content given the cost of promotion and, presently, available bandwidth. Mostly this is the result of the fragmentation and increase in the number of "channels", digital and physical, to potential consumers. Good content, by any commercial measure, is still good content but requires *recognition* by consumers in order to sell, profitably or not.

Music for everyone

Two recent "surveys" of the situation demonstrate the dilemma well. They actually both include overlap of markets for carrier sales, the "atoms", and market-projections focused exclusively on the sale of digitized files, the "bits". Because media is first about recognition of the creative expression and second about its *potential* commercial exploitation, the markets will likely complement each other. One survey points out that the early hype surrounding the sales of media over the Internet is indicative of the significant hurdles evident in profiting from on-line sales. This survey specifically notes that pricing of music on-line has little apparent commercial benefit versus the pricing of the same content available in physical retail stores. On-line sales of music reached $20 million in 1996, but gross profits stood at $200,000, the figures for 1997 are higher but likely to be even *less* profitable as competition increases [24]. MCI's highly publicized effort to promote on-line music sales absorbed over $40 million in promotion but was closed after the "top" CD sold less than 400 units [24]. Similar experience continues with such well-known examples as N2K, which recorded a stunning setback involving the download of a David Bowie single [21]. At first, when N2K offered the download free of charge several hundred thousand took advantage of the offer, but when the company began charging only few thousand opted to pay 99 cents for the single.

Even with prospects of sales reaching as high as $186 million, the survey continues, would still amount to less than 2% of overall recordings sold [24]. Others note that the major record label companies, of which six companies control over 75% of world's music revenues, will aggressively compete with on-line retailers as they seek to maximize their own distribution margins. Three of

the six major label companies, *BMG*, *Warner* and *Sony* already sell compact discs from their own web sites. Warner previously sold music through the *Internet Underground Music Archive* (IUMA), one of the pioneers of on-line music sales, in the early days of the Internet. *BMG* has recently announced work with *Liquid Audio*, a Silicon Valley start-up that has received heavy coverage in the news. But of the three, the most notable example of the future of digital distribution is *Sony*, which sells compact discs on its site at prices typically seen only at physical media music discounters choosing to compete directly with on-line retailers [25].

Although many current on-line retailers are at odds with the strategy [26, 27], it is inevitable that media companies should seek to maximize profits, as any corporation does. On-line distribution channels are available to anyone willing to devote resources to exploiting the medium. As for profits, the media company and physical carrier fulfillment company will continue to profit while increasing recognition of content that arguably suffers from less intensive promotion at physical retailers. Because so few companies dominate distribution of music and video titles, distribution is at the core of profitability [16, 25] but, absent any exclusivity in distribution arrangements it is unclear how electronic retailers of music can profit in line with the early hype. History suggests that profitability will still relate directly to the experiences of physical retailers who compete in differentiating their stores with the all-important combination of 1) price, 2) service, and 3) selection. An aside relating to successful retailers and wholesalers: in theory, it is desirable to seek to provide consumers with two of the three factors in the matrix as all three lead to little, *if any* , observable profitability in the long term.

The second short "commentary", covered by a magazine considered to be a music industry insider, discussed the great potential of digital distribution of music taking issue with the apparent frustration of consumers over relatively high compact disc retail pricing. But, the survey realistically indicates the potential for large company domination of the distribution of music digitally by the "major distributors, record companies, and artists" [28]. How these three powerful industry contingents will benefit in the aggregate is less obvious than their success with sales of physical media such as compact disc. The projected benefits to rights holders including reduced inventory and operational costs also do not seem to be obvious to all industry observers at present although the more apparent factor of reducing reaction time and time-to-market is an area of hot debate. What is presently difficult to project is the cost required to create demand of media using the Internet as both broadcast and delivery mechanism. Contrary to the hype, even the major label companies publicly recognize distribution issues: "Jim Caparro, president of *PolyGram Group Distribution*, says, 'There's so much money being spent buying real estate, there's that much less money to talk to the ultimate customer. The trend has reached an alarming level'" [29].

Content is about taste: the dictating marketing concept of "buzz", necessary to stimulate consumer demand, is a slippery beast. We believe the winners and losers for the music industry are even harder to project forward if the concept of recognition is taken into closer consideration. Will branded retailers with a history of differentiating their operations, such as *Tower Records* and *Blockbuster Video*, suffer if they become the web sites of choice to consumers who seek aggregated content? Will the major record labels fail to profitably participate if they are able to capitalize on the future buying habits of "wired"

consumers? In the past decade of physical media distribution, the major labels have successfully combined retail store promotion, radio broadcast promotion, sales support mechanisms linked to pricing, all at the same time they built successful mail order businesses targeted directly at consumers.

It is true that the early on-line music retailers can create value by attracting consumers with better information warehousing about music, on-line discographies, liner notes and electronic chats with artists, while reducing the time it takes to purchase a song (with higher, more widespread bandwidth). However, exclusivity over the copyrights and distribution rights will likely be as few and far between as with the lack of such arrangements in the distribution of physical carriers such as compact discs and video. The reasoning is sound. Media companies must distribute their content as widely as possible to create the demand for consumer purchases. No single retailer can claim a monopoly over purchasers. Thus, media companies should be expected to continue to seek ways to reached aggregated numbers of consumers in an effort to profit. Broadcast is a necessary ingredient to the success of music, the Internet provides both a broadcasting and distribution channel rolled into one. The unanswerable question remains: how quickly do the copyright holders have to act to succeed in this potentially lucrative new age of digital distribution?

A note: The Artist, formerly known as Prince, recently entertained potentially restricted distribution of his latest work to Best Buy, as "sole distributor". Speculation about the eventual enlistment of a music wholesaler, a "one stop", in industry parlance, to provide more widespread availability to the marketplace was recently answered in a decision to release the album to a major wholesale

group. as well as other retail chains .The album is not yet released at the time of this paper. Buzz? Smart marketing? Profit incentive?

Nonpassive media: Images

Other content with copyright security concerns that directly relate to currently available digital watermarking technology include still images and video. Offshoots of embedded signalling in the near future may also protect books. How music differs from video, or even still images, relates directly to the number of available broadcast opportunities afforded musicians. Music, a passive media, can easily be market-tested by live performance and radio play, which also have associated legal rights: performance rights and broadcast rights. Applications of digital watermarking consistently extend to these rights, much the same way they do presently, if we concern ourselves solely with establishing responsibility over copies of the original expression. Further discourse on copyrights below will describe limitations of digital watermarking, and technology in general, when seeking to provide copyright protection.

A more commercially relevant issue for passive media such as music is actually the market behavior of consumers, who may listen to a music recording [30] with high frequency. This behavior makes the cost per listen relatively tiny to consumers over time versus the frequency of mass consumers in viewing a video or image. How many times do consumers view a video or even a broadcast of a sports event versus a song? How much is the commercial value of individual photographs in a *Playboy* magazine if the magazine is published with new sets of photographs every month? Why do we listen to the same songs repeatedly? Some of these questions are better left to philosophical discussion, which is treated below.

Still images, like videos, are nonpassive media but their time value is also speculative, in the commercial valuation sense. By this we mean that the highest prices paid for images tend to be for paparazzi photos whose value over time quickly diminishes. Other commercially viable images also relate directly to the newsworthiness of the photograph in question. Additionally, the sheer number of people able to photograph, versus creating other content, puts pressure on the valuation of any particular image. Supply is far greater than demand. At the same time, there are many ways in which we are able to manipulate and use images: news reporting, events, forensics, medicine, travel, etc. A picture *is* worth a thousand words and assists us in communicating via visual observation. We do not believe it is adequate to use valuations of images of famous artistic expression, such as the *Mona Lisa*, without proper market-based approaches, as the value is bound by both the recognition of the work and the medium itself. The market more highly values the original expression; for instance, i.e. the paint on canvas, based on the medium not copies thereof, i.e. posters.

This does not mean libraries of reproductions of famous images are without value, only that digital copies in the aggregate must command pricing that is set by market mechanisms. We can estimate the value of a well-known image by considering the number of books that include the work, the number of postcards, the number of tee shirts, and related media sold containing the image. Any number of uses that extend into a large number of items, which may be used, marketed, and sold, assist us in determining commercial value. Commentary that copyright is outmoded [31] alone cannot settle the commercial issues important to artist's [32]. More to the point, if we can charge for media,

we do. If technology is able to assist in the realization of profitable commercial activity, digital watermarking being the example technology in this paper, we can expect content creators to demand it. Example licensing arrangements, such as the licensing of *Norman Rockwell* images for commercial use, are negotiated on a case-by-case basis with the archive or estate that holds the copyrights over such works [33, 34]. These estates are in direct control over the works and derivative works containing the original expression and its likenesses and have a wide range of nongeneralized behavior with respect to exploitation of the original expression in question. We do not concern ourselves here with more detailed analysis, leaving this to others in respective and related fields, only the thesis that recognition can be created with time and money and identifying ownership of the original expression is necessary to effectively capitalize on copies subsequently sold [35].

A direct result of profit seeking, many artists necessarily seek recognition. Recognition afforded artists at minimal cost because of market tendencies, which are difficult to predict, serendipity or fad, increases the potential estimable demand by rightsholders to efficiently identify ownership and responsibility over copies. This establishes the reason media companies seek digital watermarking technology. If the work is commercially valuable, as demonstrated in profits exceeding costs of promotion and distribution, these parties are likely to want to capitalize on consumer demand for the works and any derivative relating specifically to the original expression.

What is art ?

This still leaves us with the question of what constitutes a "commercially-valuable work" versus an "artistic masterpiece". Is there a difference? A few recent articles pose the same question. An interesting work touches on the subject although the debate will not be easily settled. Market researchers and conceptual artists, Vitaly Komar and Alexander Melamid, polled 1001 Americans about what they "liked in a painting" [36]. They further researched a sample of people in other countries said to represent over two billion people around the world. With this research they published the book *Painting by Numbers: Komar and Melamid's Scientific Guide to Art* which presents works by Komar and Melamid reflecting data compiled in their research. What they found was that the polled adults had a disposition to the color "blue" by 44 percent and that while half the sample wanted famous people in the pictures the other half wanted ordinary people [36]. Is there then a difference between high art and popular taste? It is fair to argue, that artists do not all create only what potential consumers "want" but then again some artists do. Throughout history, artists have parodied the situation. Besides claiming that "great artists steal", even Picasso said people did not pay for his pictures only for his "signature".

Broadcast, dollars, and recognition

Next we observe some cursory data on other media, although there is almost certainly no definitive answer to the question of predicting successful market valuation of artistic expression. The issue is fueled by the fact that artistic expression from a commercial perspective has a measure of "speculative value". An arguably more market savvy industry may elucidate the complicated

issue of market valuation of content if we consider the recent bidding of US television programming. While television broadcast has undergone vast changes in distribution as a result of the success of cable television and an increase in the channels and number of programs available to consumers at any given time, what has resulted? First, the major broadcasters have suffered a decline in overall marketshare from over 90% to less than 50 percent of the viewing audience during the course of the successful deployment of cable systems in the past 25 years across the United States [37, 38]. However, so-called "prime-time" television gives the four major broadcasters, *ABC*, *CBS*, *NBC*, & *Fox*, a share of over 60 percent of the viewing audience [37].

The broadcasters' ability to aggregate viewers gives them the highly valuable ability to charge higher advertising rates. Advertisers, of course, are concerned with creating recognition for their *own* products and services. *Seinfeld*, the *NBC* show "about nothing", that was originally given a traditionally low number of pilots to prove itself, commands advertising rates as high as $500,000 per 30 second slot [37]. Because *NBC* will lose the show and thus its valuable command of high advertising rates during the viewing time slot, the broadcaster decided, "forced" [37], to pay six times the rate it currently pays for another of its popular programs, *ER.* A separate, but related, bidding yielded $18 billion to the *National Football League* for football broadcasting rights over the next eight years. After decades of broadcasting the sport, *NBC* was outbid and will not broadcast the sport demonstrating the commercial value placed by broadcasters of aggregating viewers [37]. Commercial consideration or high art?

Distribution control and technology

Convergence is where this paper originates, but the concept is inherently difficult to characterize. How media valuation relates to the concept is apparent in the issues thus far discussed: how to profit from it is far less clear. While digital watermarking can only provide a means for establishing responsibility, why is the technology necessary from a commercial media valuation perspective? Many of the most powerful media and technology executives have been meeting at an annual conference sponsored by the investment group *Allen & Company*. The most recent conference indicates a growing debate over just how technology can benefit media companies [39].

While technology leaders have accused media companies of failing to adopt the alternative of digital distribution of media more quickly, it is still unclear how electronic distribution of content will give media companies higher profitable sales. This assumes the absence of more realistic copyright security or the ability to identify consumers via the vehicle of the content itself, through better monitoring of viewing and listening habits. Certainly secure digital watermarking will assist in the distribution and monitoring of both broadcast and sales of copies of content, but other issues indicate more fundamental requirements by media companies [32]. The technology companies, and their consumer electronic brethren, appear more focused on their own goals, namely selling faster computers and software, both new products and improved versions.

Too many early pronouncements about the benefits of technology have been proven wrong while the issue of further erosion of the ability to "control"

distribution and its related profitability continues unabated. At the heart of the debate, we believe, is the difficulty of media companies to consistently predict what will be commercially-successful, inherent in the media business, and the desire of technology companies to benefit from potential consumer demand over alternative media distribution platforms such as the personal computer (PC). PCs are potentially lucrative platforms in which to distribute and exchange content. But, the seamless and perfect nature of copying media without any control over its subsequent, unauthorized redistribution is a realistic concern to media companies, which exhaust time and money in differentiating media products from the growing number of "potential hits" [13, 21, 22, 24].

A huge audience of consumers, limited only by accessibility to a PC and bandwidth to facilitate more competitive acquisition of desirable media, represents, in parallel, an increasing number of "potential pirates". Statistics indicate a growing increase in piracy of music [40], and its dramatic impact on the profitability of media companies [41, 42]. There is no guarantee of a version 2.0 of a hit song or video. The "early dawn" of the Internet quickly lead to many technology companies to dismiss the concept of copyright in an age of perfect and endless copying, sowing the seeds for the present debate over the merits of technology to assist in profiting the owners of content [31, 32]. Another angle on the debate is the faulty presumption, by technologists, that consumers, who necessarily have a limited period of enjoyment time, when sleep and employment are factored in, will not continue to seek passive entertainment and purchase carriers such as compact disc, video, movie tickets, and any number of "atoms" comprising the media "bits".

This, although many "promising" technologies have yet to demonstrate commercial viability, including consumer-control over movie storylines, viewer-control over sports event viewing angles, *PhotoCD*, 500 channel television, ISDN, *WebTV*, and any number of technical "innovations". It is a fair argument that technology has increased the need for better approaches at marketing [43, 44]. Although *Betamax* was a failure for *Sony*, its small size relative to VHS and *Sony*'s traditional strength at miniaturization almost certainly were reincarnated in the successful 8-mm format introduced years later. While *Sony* was able to capitalize on its failure to create the standard for a home video recorder format, are unsuccessful attempts to further media distribution an indication of poor technology or simply products introduced too early in the long march of convergence?

Time value of media as it relates to piracy

A given media work still must adhere to typical financial analysis which includes the distribution mechanism chosen. For broadcast, the revenues relate directly to the ability of the broadcaster to sell advertising time. The area of advertising extends beyond television and includes radio, newspapers, magazines, billboards, and cinemas. Ultimately the media distributed may require pricing of broadcast or performance rights not solely copyrights. To simplify this thesis, we limit the legal observations to copyright, where over a longer period of time copies of the original expression may command significant returns on the cost of the copyright. Of the numerous ways to value the work, lessons from valuing real estate are instructive to most business valuation approaches. The general categories include: 1) market approach; 2) asset-based approach; and 3) income approach.

The market approach takes similar "businesses" and uses comparative value for analysis. The asset-based approach, also called the cost approach, takes components of a "business" to sum up the parts to derive the total value of the business. While tangible assets are easier to value, intangible assets, such as media, do not lend themselves to ready calculation. The income approach, or investment value approach, divides a rate of return by expected future income. The term "capitalization" relates to this valuation method.

We focus on the income approach as it best captures the task of any media company in projecting the potential worth of a given media property. However, market and asset-based considerations complement income analysis by creating relevant benchmarks for making assumptions about the ability to fully realize a valuation. Other factors weigh into the valuation. We summarize these for consideration but only touch on the subject as it is as much of an art as a science. Relevant factors, identified by Internal Revenue Service Ruling 59-60, are described for business appraisers seeking to form opinions about the value of closely-held companies, helpful for our purposes. 1) Nature and history of the enterprise; 2) General economic outlook as well as industry condition and outlook; 3) Book value of the stock and financial condition of the business; 4) Earning capacity of the company; 5) Dividend paying capacity of the company; 6) Existence of intangible assets or goodwill; 7) Sales of stock and the size of stock to be valued; 8) The market price of corporations engaged in the same or similar line of business whose stocks trade in an open or free exchange or over the counter.

For large media companies engaged in active sales of media products we are able to estimate the value of the corporation. As specific media properties comprise the enterprise in the aggregate, analysts are able to identify in a very imprecise way, the potential value of a new release of media. The costs may be well understood; the future revenues are highly speculative. Again, venture capitalists share the same risk factors.

"Common sense" is important under these valuation methods and is set forth as an important aspect of valuation. In addition to Ruling 59-60, Ruling 68-609 is taken into consideration for valuing intangibles when better methods are not available. Indeed, although these concepts are founded in methods used to analyze the value of a business, they illustrate the dilemma of all media companies: how are new media products valued absent any market testing or income stream? On the other hand, media is commercially viable and even valuable if consumers demand the content [16]. As all corporations, media companies should "[a]ccept investment opportunities offering rates of return in excess of their opportunity cost of capital" [45]. The tools for estimating a discounted cash flow rate of return or an internal rate of return, which may be misleading under certain conditions when compared to a net present value calculation, are as follows:

True rate of return on an investment, which generates a single payoff after a one-year period

$$\text{Rate of Return} = \frac{\text{payoff}}{\text{investment}} - 1$$

For Net Present Value (NPV) we seek to make investments which where NPV exceeds 0. Where a discount rate makes NPV = 0 we arrive at our rate of return as well. The discount rate is the cost of money.

$$NPV = C_0 + \frac{C_1}{1 + \text{Discount rate}} = 0$$

Where C_1 is the payoff and $-C_0$ is the required investment.

Why do we throw in a financial equation into this section? Simply to elucidate the fact that required investment, the actual cost of creating and distributing the media, a budget, is easier to project, although exceeded often enough, than the *likelihood* of a payoff. We also know what the cost of borrowing is since we can ask a bank, seek out money from others, or look at the borrowing rate on credit cards, as some artists and businesses do in finding innovative ways to finance their work. What is speculative is the payoff. Using some of the criteria evident in any business valuation, speculative risk can only be *estimated* based on economy-wide factors, industry factors and business-specific factors, time is critical to this analysis. Especially in cases where the funds used to create media works are borrowed [46]. Some artists and media companies value their work higher than is justified using financial valuation models. Although many would value their work without any consideration of these factors, even with lots of "buzz", the marketplace will ultimately determine the payoff.

We can make observations about time value of content, which relate directly to market valuation of the same content. Generally, the time value of a still image is considerably less than the typical time value of a given album release, which achieves over 75 percent of its revenues within two months of release [13, 19, 21]. This applies to as much as 90 percent of music products with the exception of the relatively few long sellers and hit releases [21]. Conversely the hits, perhaps less than 1000 titles in any year, comprise the majority of revenues in

the music industry [21]. In video, the top 20 films enjoy over 80 percent of the market [47]. While the time it takes for a movie release to be released into video "channels" indicates the reduced value of the movie in the theater "channel", both music labels and movie studios share concern of pirated works interrupting these copyrighted works' revenue "peaks".

Piracy is necessarily about profit motive. Unfortunately, piracy, viewed as a type of black market, is an inexact measure of the value or demand of media. Widely recognized and available media, which is not pirated, has less demonstrable commercial value. The pirates seek a time and cost advantage in distributing unauthorized content. In fact, piracy accounts for over 789 million cassette and compact disc units in the top ten countries annually [41]. Recapturing even a portion of the piracy market would amount to a significant increase in revenues for the music companies [41]. Motion picture studios have had similar experience with piracy. A counter argument made by some analysts is that piracy is a response to the high price of media [42]. While still others insist [19, 20, 21, 22] that figures for piracy fail to take into account the immediate recognition afforded content creators which leads to subsequent sales of the authorized media [42]. As all consumers do not have the same disposable income but may seek enjoyment of the same media, relative pricing for content is an area of great interest to those seeking to reduce piracy *and* those, namely proponents of digital distribution, seeking ways to sell media in disintermediated forms [28].

The cost to catch and prosecute pirates has escalated. The increasing detrimental impact on the media business is well known. Differentiating between casual piracy, of which home video recording of television broadcasts

is a representative example, and hardcore piracy operations, such as black market compact disc replicators, has become blurred with the advent of multimedia PCs and high speed connections to digital networks. Education of consumers is but one invaluable weapon against piracy; while, depending on the market and the media, most consumers still choose to purchase authorized works. The Internet is an anonymous marketplace where pirates, under the constraint of selling to consumers when media is commercially viable, typically use price alone or the absence of price to attract consumers, these same pirates effectively attract rights holders and their agents. It is not unforeseen that monitoring activity will become more difficult as bandwidth enables consumers on the one hand to download media in real time or better, the lessening of this same time constraint will allow pirates faster time to consumers seeking unauthorized media. Given this, it is unlikely we will avoid a vast game of cops and robbers in the digital distribution of media [48].

Other media battlefronts: DVD v. Divx

We have focused primarily on mature consumer markets for digitized media, but offer some comments on the consumer electronic format that has drawn considerable attention, digital versatile disc or DVD.

It is unlikely the major media companies will ignore any perception of insecurity when considering new technology. The growing controversy between digital versatile disc (DVD) and *Divx*, a rival technology which is "controlled" over phone lines plugged into the *Divx* player, illustrates the core concerns of entertainment companies. *Fox's* decision to join *Paramount*, *Universal*, *Disney*, and *DreamWorks* in supporting Divx, is a strong indication that major studios

remain unconvinced at security efforts proposed by consumer electronics companies and related technology interests. This, notwithstanding recent announcements by *Intel* and a number of large Japanese consumer electronics companies. *Warner* remains a Divx holdout, while *Disney* and *Universal* support both formats. "Many studio executives have complained that even a 'secure' DVD title remains vulnerable. To them DVD's ease of use translates to lack of security" [49, 50]. While consumers remain unsure as to what the DVD format is [51], comments by the acting head of *20th Century Fox Home Entertainment*, "'Given the significant anti-copying safeguards that Divx offers, we feel our film assets will be sufficiently protected to allow for their simultaneous release with VHS'" [49, 50].

The demands of copyright protection are enormous. Requiring on-line companies to authenticate digitized media, as they do with physical media, will become a necessary component in the fight against piracy. Active registration and enforcement of copyrights by content creators will become a more invaluable activity. Digital watermarking has come to be seen as a form of insurance in the fight against piracy; but, only under implementations, which enable third parties to confidently, authenticate the content. A result of cheap digital distribution, another "obvious" answer to piracy is to restrict what may be done with media-based content files on a PC. This of course, would be the *easy* but *wrong* solution, as we turn to the issue of copyright.

Money trail Content creators and publishers seek to maximize revenue per unit sold or broadcasted.

Digital watermark requirements It is difficult to predict market acceptance and subsequent piracy, however, the watermark must be robust enough to survive

the various manipulations content undergoes while distributed and broadcasted in order to provide a effective tool for monitoring market reactions. For a given media work's actual security this relates closely to the period of time when the highest aggregate of sales are expected to occur. In the longer term, when the content may be less commercially valuable, the watermarks can act as an audit trail of how the media has been exchanged. Time value of the content is an upper bound on the appropriate cost of implementation of digital watermark security when considering the potential commercial value of the media to be protected. Although most available digital watermark technology is incapable of third party authentication of content, insisting on such authentication, common in physical media distribution, is likely to be a fundamental requirement in an age of digital distribution.

"Original Work" - Copyright or Wrong

It is prudent to give a cursory outline of copyrights, which many fail to understand. *We do so not in the interests of providing any form of legal advice, only to provide relevant limits for consideration to the area of technology when applied to protection of intellectual property.* The additional bundle of rights which also relate to digital watermarking are performance, broadcast, and mechanical rights, etceteras. We concern ourselves mostly with "reproduction" as a matter of convenience. We also concern ourselves with *United States Copyright Law* and recognize the disparity between copyright law and related laws in other countries.

As with all US laws, Congress first enacts legislation but it is the Courts which provide judicial oversight and interpretation of the law. Because copyright is exceptionally difficult to characterize, discussion of a number of legal cases will help in elucidating what a digital watermark can be expected to accomplish. As explained previously, it is not possible to, on the one hand, seek to maximize

exposure and commercial exploitation of creative works, and on the other hand, expect no attempts at piracy.

Copyright law is established in the *United States Constitution*. "Copyright" is the only occurrence of the word "right" in the Constitution. Over time, legislation has been adopted making copyright more consistent with advances in technology. In advance of technologies to distribute digitized content across networks, such as the World Wide Web, other technical innovations created legal impetus for a number of publicized suits concerning intellectual property and its protection. Of particular note was *Sony Corporation v. Universal City Studios* (1984) concerning the sale of videocassettes recorders (VCRs). The Supreme Court ruled that "[b]ecause recorders were 'widely used for legitimate, unobjectionable purposes', the recording did not constitute direct infringement of the studio's copyrights.... Absent such direct infringement, there could be no contributory infringement by *Sony*" [17]. The key factor being that there was private not commercial use in recording. While citing the concept of "fair use", which protects consumers from *some forms* of copyright infringement, the debate did not end with this ruling. Indeed, the concept of "fair use" has been extended to areas not previously anticipated, including reverse engineering of copyrighted software. While covering legal issues that are not directly related to copyright, we will discuss cases to illustrate other potential legal arguments potentially relating to widespread adoption of digital watermarking as a means for copyright enforcement. Some of the better-known cases include, *Atari Games Corp. v. Nintendo of America, Inc.* and *Sega Enterprises Ltd. v. Accolade, Inc.* The legal issues in these cases, in part, concern boundaries of copyright while addressing attempts at protecting the creator of a work versus the intent of *US Copyright Law* .

Interestingly, although commercial monopolies are thought to be illegal, in most industries in the US, a particular form of "public monopoly" is actively protected by the law, that of patents. The apparent incongruity relates directly to both legal and economic analysis of just what constitutes intellectual property and the many designations that exist for various creative works. Patent law does proscribe higher standards for the issuance of a patent, and also limits the term of protection. This period of protection is shorter than protection offered for other intellectual property such as copyrights and trademarks. Definitions are helpful in providing a framework. *United States Code*, *Title 17 (Copyrights)*, *Chapter 1. (Subject Matter and Scope of Copyright) Section 101*, provides for the following amongst a list of additional definitions *(emphasis added)*:

> A work is **"created"** when it is fixed in a copy or phonorecord for the **first time**; where a work is prepared over a period of time, the portion of it that has been fixed at any particular time constitutes the work as of that time, and where the work has been prepared in different versions, each version constitutes a separate work.
>
> A **"derivative work"** is a work based upon one or more preexisting works, such as a translation, musical arrangement, dramatization, fictionalization, motion picture version, sound recording, art reproduction, abridgment, condensation, or any other form in which a work may be recast, transformed, or adapted. A work consisting of editorial revisions, annotations, elaborations, or **other modifications** which, as a whole, represent an original work of authorship, is a "derivative work." [52]

Those interested in more specific information or interpretation of the law, should seek out legal advice, for our purposes these definitions provide important clues concerning how digital watermarking technology can potentially assist copyright holders. While we can describe a cryptographically secure means for tamperproofing copyrighted media works, so that the original work is preserved up to the point that manipulations create an invalid digital watermark and, thus, a *possible* derivative work, we must exercise some caution, insisting that all digital watermarking technologies are not equivalent. We must be careful in also indicating that "damaging" a digitized media work, in an attempt to erase watermarks, even if this can be argued as "other modifications", does not seem likely to establish a "derivative work." The core issue of copyright regards elements of creativity. However, failure to implement some form of "nonrepudiation" or "provable authentication" into a digital watermarking process is bound to result in faulty claims about some implementations of the technology that cannot establish a technical baseline of what information, represented by digitized samples, constitutes the original work. There will no doubt be ongoing debate, legal and otherwise, which will provide an even better framework than is possible in this paper. However, when one has a copyright, what exactly does that mean?

The economics of legal fair use

Essentially, a copyright is a form of contract between the creator of the work and the public. While based on the recognition of property rights, the creator agrees to make his work publicly available in consideration of legal recognition that law, ultimately subject to the interpretation of the courts restricts any use of the work by others. The *Constitution* promulgated copyright law in the interests of

promoting science and the arts. One helpful commentary explains this in a succinct manner *(emphasis added)*:

> "Fair use" is a doctrine that permits courts to avoid rigid application of the copyright statute when to do otherwise would stifle the very creativity that copyright law is designed to foster. **The doctrine of fair use recognizes that the exclusive rights inherent in a copyright are not absolute, and that non-holders of the copyright are entitled to make use of a copyrighted work that technically would otherwise infringe upon one or more of the exclusive rights. Although fair use originated "for purposes such as criticism, comment, news reporting, teaching, ... scholarship, or research," it also applies in other areas,** as some of the examples below illustrate. However, courts seem more willing to accept an assertion of fair use when the use falls into one of the above categories. Perhaps more than any other area of copyright, fair use is a highly fact-specific determination. Copyright Office document FL102 puts it this way: **"The distinction between 'fair use' and infringement may be unclear and not easily defined. There is no specific number of words, lines, or notes that may safely be taken without permission.** Acknowledging the source of the copyrighted material does not substitute for obtaining permission." The document then quotes from the 1961 Report of the Register of Copyrights on the General Revision of the U.S. Copyright Law, providing the following examples of activities that courts have held to be fair use: - Quotation of excerpts in a review or criticism for purposes of illustration or comment; - Quotation of short passages in a scholarly or technical work for illustration or clarification of the author's observations; - Use in a parody of some of the content of the work parodied; - Summary of an address or article with brief quotations, in a news report; - Reproduction by a library of a portion of a work to replace part of a

> damaged copy; - Reproduction by a teacher or student of a small part of a work to illustrate a lesson; - Reproduction of a work in legislative or judicial proceedings or reports; - Incidental and fortuitous reproduction in a newsreel or broadcast, of a work located in the scene of an event being reported. [52]

For our purposes it is not necessary to interpret the large body of legal argument surrounding fair use; but it does place important limits on just how far technology can extend in protecting copyrights. Certainly the PC is a device used for the conception of original works as well as activities which could be characterized as derivative works creation. Image, audio, and video manipulation, modification, or editing software is widely available.

Is all original expression copyrightable? While copyright previously concerned "sweat of the brow" (in *Feist.*), a modicum of creativity has been the more stringent standard for establishing copyright. We again seek an understanding of fair use, *Lotus Corporation v. Borland* is somewhat instructive *(emphasis added)*:

> In *Feist* [*Feist Publications, Inc.* v. *Rural Telephone Serv. Co.*, 499 U.S. 340 (1991)], the Court explained:
>
> The primary objective of copyright is not to reward the labor of authors, but to promote the Progress of Science and useful Arts. To this end, **copyright assures authors the right to their original expression, but encourages others to build freely upon the ideas and information conveyed by a work.**
>
> *Feist*, 499 U.S. at 349-50. We do not think that the Court's statement that 'copyright assures authors the right to their original expression' indicates that

> all expression is necessarily copyrightable; while original expression is necessary for copyright protection, we do not think that it is alone sufficient. Courts must still inquire whether original expression falls within one of the categories foreclosed from copyright protection by 102(b) [53].

Attempts at restricting the activity of derivative work creation have led to the increase in use of both economic and technical tools.

Some legal research has focused on the use of "tying arrangements", presently a violation of the *Sherman Act* [54]. Though not a copyright issue, in the strictest sense, it will help to look at this concept. In essence, hardware and software companies fear the process of "reverse engineering" which may allow others to recreate a particular device or software application in such a manner as to deny the originator control over their product's commercial exploitation. While software companies insist that such activities violate their copyrights over the source code, the written instructions comprising executable code or actual software application, the courts have notably restricted interpretations of copyright indicating such arrangements are more properly the subject of patent rights, an entirely distinct form of intellectual property, legally separate from copyrights.

We will attempt to demonstrate previous attempts at restricting copyrightable material, although these cases more correctly relate to the dichotomy between "ideas" and "expressions." The following cases introduced copyright issues that were entirely separate from the tying issues that are explained. The tying arrangements in the *Atari Games Corp. v. Nintendo of America, Inc.* and *Sega Enterprises Ltd. v. Accolade, Inc.* related specifically to the nature of the video

game industry and use of proprietary means for packaging the game— in some cases, on specially-manufactured cartridges. "Copyright protection extends to the expression of ideas, but not to the underlying ideas" [54]. Why this matters relates to the preferred design of a digital watermarking system which, in and of itself, is able to provide for a provably secure means of establishing ownership over a copy of an original work. Inevitable reverse engineering and related attempts at circumventing security increases the perception that tagging the digitized signals representative of the original work may be the most fundamental way to provide layered security. We believe that within the framework of this paper, the *actual* original work, which can be copyrighted, can be equated in digitized form as those perceptually-significant regions in the signal that can be securely watermarked with human-readable text. The elegance of this approach requires some further understanding of copyright but also relates to the next section concerning cryptography.

As we extend further into how the courts determine fair use privilege, we find further guidance in *Section 107 of the Copyright Act of 1976*, although the relative weights of the respective factors are not provided:

> Four factors must be considered (1) the purpose and character of the use, including whether such use is of a commercial nature or is for non-profit educational purposes; (2) the nature of the work; (3) the amount and the substantiality of the portion used in relation to the copyrighted work as a whole; and (4) the effect of the use on the market value of the copied work. [54]

Looking again to reverse engineering in the *Atari* case, the "... court specifically recognized that reverse engineering software from a lawfully obtained copy constitutes fair use" [54]. Much speculation can be made on similar contentions

that content lawfully obtained in a "locked" form and subsequently reverse engineered to allow manipulation of the work may also allow persons to circumvent various forms of security designed to protect copyrighted works. *Nintendo* developed an authorized game cartridge which has a software "key" which unlocks the game console to enable the game to be played, while unauthorized cartridges lack this feature. "... [T] he court determined that copyright did not preclude others from delving into the program to learn its underlying ideas" [54]. In fact, as mentioned earlier, "[t] o hold otherwise, the court suggested, would allow the author to acquire exclusive rights in the facts, ideas, processes, or methods of operation in the copyrighted work, and thereby encroach on the territory of the patent law" [54]. Essentially a determination of what' s protected by copyright, expression, versus our earlier discussion on fair use of expression.

In a somewhat different attempt at circumventing a security feature, *Accolade* reverse engineered the *Sega* security system and wrote a development manual which successfully mimicked *Sega*'s own gaming environment. *Accolade* was able to create games for *Sega*'s consoles, without having obtained a license from *Sega*. Although "[t] he *Sega* court expressly rejected a per se right to disassemble object code ... [the court] held that disassembly of copyrighted object code constitutes fair use if 'disassembly [is] the only means of access to those elements of the code ... not protected by copyright and the copier has a legitimate reason for seeking such access' " [54]. It is this argument which will strongly influence the effectiveness of digital watermarking architectures while ensuring legitimate access to watermarked original works. Basically, if the access is legitimate, restriction may be legally difficult to defend.

Because *Atari* and *Sega* provide a rich basis for considering security of copyrights attained through technology, they are instructive of how legal issues serve as restraints on how much control the copyright holder may exercise on others seeking fair use of the copyrighted works. The form of security implemented by *Nintendo* and *Sega* to "tie" users to games solely authorized by *Nintendo* and *Sega*, respectively, may effectually restrict others from freely entering into the market. From an economic standpoint, the time required and cost to implement, and subsequently circumvent these types of security measures, would render this ineffective.

Copyright is designed not to prevent further development of science and the arts, but are monopolies that are reigned in to reduce the barriers to entry and encourage new industries and new firms to enter these industries. When taken from an economic perspective, the courts are simply recognizing the *necessity* of advances in a particular field that has the greater potential of benefiting society as a whole. With regards to the software industry, the courts recognize that tying arrangements may have more detrimental consequences than similar arrangements for commodity items. Which explains the difficulty in attempts that seek to use copyright to protect "ideas" instead of "expression." "[T] he monopolist's control over the software market is absolute: The monopolist has a proprietary critical resource that a competitor cannot 'invent around'" [54].

First sale doctrine: Whose responsibility is it ?

Fair use guidelines provide useful boundaries to any consideration of the rights of copyright owners. When the copyrighted material is distributed widely in the process of attracting commercial demand, however, we need to explore just

what legal ramifications exist for copyright holders who are not compensated. Having differentiated between original and derivative works, there exists the potential that digital distribution opens additional legal issues. While we anticipate this area to continue to evolve, given the concerns of the many interests involved, we will try to describe some of the potential conflicts inherent to the distribution of copyrighted content.

In the world of physical media distribution, there are many channels available, both for broadcast and carrier sales. Specialized retailers, such as *Tower Records*, compete for consumer sales by differentiating their efforts from other retailers, as described in the earlier section discussing the marketing of media. Written content and imagery attracts consumers to publications, such as magazines; spoken content and music selection attracts consumers to radio. The number of possible combinations of content and editorial material provides for rich broadcast opportunities, which have the effect of attracting advertising dollars to the broadcasters. Publications, including newspaper and magazine, may have differing time value to a consumer, but they too seek advertising to support their commercial efforts. Total spending on advertising has continued to grow over time [55], although the ability to reach an aggregated group of consumers has grown more difficult.

The argument that there is too much entertainment vying for consumers' dollars is beginning to take shape as media and entertainment companies seek profitable markets for their copyrighted material, while trying to maintain distribution control [56]. How do on-line companies attract consumers? Do they seek advertising to support their electronic franchises? The answers relate directly to answers we find in the real world. On-line business is increasingly

dependent on advertising as well as the availability of *desirable* content. We discussed this issue earlier, but reiterate it in the belief that legal remedies sought with real world copyright infringement, are starting to be reflected in legal actions against companies and individuals offering content on-line.

An early example of the legal wrangling concerning on-line availability of copyrighted material was the suit by music publisher, *Frank Music*, against *CompuServe, Inc.,* a large on-line provider. The *Frank v. CompuServe* suit was settled with *The Harry Fox Agency* (HFA), the licensing subsidiary of the *National Music Publishers' Association, Inc.* (NMPA). With the contention that on-line providers have a profit motive to attract consumers by what content is available on their servers, the computers that archive files to be accessed on a network, HFA sought to establish some precedence in linking on-line copyright to physical media copyrights. *HFA* agreed to license *CompuServe* forum sites to permit uploading and downloading of copyrighted recordings of songs. *NMPA/HFA*'s president indicated both the intent of the suit and its subsequent settlement: "I am extremely pleased that the settlement announced today may lead to a broad industry practice of licensing musical works utilized by on-line computer services. It is our hope that the other services will now come forward to license works on a similar basis as soon as possible, obviating the need for further legal actions" [57].

The audio industry has been diligent in enforcing its copyrights by other legal actions taken against sites that allow for downloads of copyrighted music [42, 48]. Although active monitoring is far less costly than enforcement, as explained elsewhere in this paper, much copyrighted material is not registered nor are there efforts by some rights holders to enlist the assistance of agencies, such as *HFA*, to actively pursue infringers. The problem arising from the

inability to collect damages for copyright infringement which has occurred prior to registration of the copyright. Some of this behavior relates to the actual commercial value of the works to be protected, i.e. works with little apparent commercial value, being deemed less than the cost of monitoring and enforcement.

While we addressed this analysis earlier, it is important to recognize other areas of law, which further limit the recourse available to copyright holders. Whereas previous threats of legal action lead to the adoption of the *Audio Home Recording Act of 1992*, and subsequent additions to *United States Code Title 17 Copyrights Sections 1001-1010 (Digital Audio Recording Devices and Media)* [17], compromise was ultimately reached because royalties are assessed on both the recording device and the recording media, divided between songwriters, publishers, record producers and recording artists. Besides previous discussion of perceived monopolistic pricing by the major record labels, another important consideration for better defining digital watermark security relates to the sale of used copyrighted material under the "first sale doctrine". If we can determine that copyrighted material, which has been downloaded by a consumer, is still the original work, through subjective evaluation or by tamperproofing the original digitized samples with a secure digital watermark system, can we limit the subsequent resale of the work to others by the owner? This area has become increasingly difficult to resolve economically, with the steady rise of retailers willing to purchase used compact discs from consumers; legally, the answer may be lie in an overview of the legal framework of the "first sale doctrine".

Notable among the industrialized nations, Japan allows the legal rental of compact discs while limiting the start of the rental activity. An album released by domestic artists may legally be put on rental shelves within a few weeks of the album's release, while foreign repertoire may only be released to rental stores one year following the album's release date [19]. In the US, resale of used CDs, is considered to be a form of rental activity [17]. The concern of copyright owners regards the durability of the CD versus items such as books, which become worn, or the vinyl record, the CDs predecessor carrier and another media subject to wearing [17]. What is of particular importance to the issue of on-line resale is the fact that resale of used CDs "is not covered by current federal copyright law royalty provisions" [17]. Although this has been partially remedied by the establishment of mechanical rights in the US, the issue remains unsettled from the perspective of major label companies as well as their brethren in other related industries [13].

Because resale of used CDs may constitute circumvention of the *Record Rental Act of 1984*, further analysis is required. A matter of market impact, the resale of used CDs could reach a highly significant share (20%) of the music industry's revenue [58]. Surveys conducted a few years ago by *SoundScan*, a company engaged in market data gathering, and the *National Association of Recording Merchandisers*, confirms the concern held by rights holders [59]. Although the same survey also substantiates the claim that consumers sell their unwanted CDs in order to purchase more CDs [59], we must not confuse the issue for potentially greater negative impacts with digital copying over networks.

The parallel concern for this activity in the digital domain is less apparent as currently available technology is limited by bandwidth and compression, i.e.,

most available audio content on the Internet is not the commercial quality evident in compact disc [50]. Backing analysis that indicates major label companies should not rush to distribute their content digitally, most valuable copyrighted material is not yet made available on-line [50]. This confirms discussion in this paper, it does not indicate how the issues will dramatically change as downloading times and quality cease to become barriers. Ultimately, with the *Record Rental Act* and other subsequent rulings by the courts a balance in favor of copyright holders has historically been created [17]. Arguments in favor of resale royalties have been presented; but further action, legal or other, on many levels will undoubtedly be required.

> The recording industry controversy is not the first context in which the payment of royalties on the resale of creative products has surfaced. Most notably, the enactment of the Visual Artists' Rights Act of 1990 ("VARA") brought this same issue to the forefront of the debate over the amount of protection to extend under U.S. copyright law to visual artists for their works of fine art. [17]

Implementation of a workable system to enforce rights will demand diligence.

> Copyright laws exist to encourage creative and scientific efforts that enrich and benefit the public. Congress has determined that the best method to encourage these efforts is to provide economic incentive for creation. Copyright protection has always balanced artists' needs for fair remuneration for their creative endeavors with the public's intuitive sense that once a tangible item is lawfully acquired, the owner's property rights to the item should abrogate any rights of the copyright owner. However, within most of the monopolies afforded to copyright owners- notably, reproduction, adaptation, and public performance- this is not the case.

> Since technological advance has once again opened up the potential for exploitation of a right normally vested in a copyright owner, it seems fair to consider the copyright owner's interest in participating in the exploitation. This conclusion is particularly sound in light of other significant exceptions to copyright limitations, such as the Record Rental Act, that Congress has adopted.
>
> Despite the fact that a resale royalty scheme for works of visual art may currently be unworkable on a federal level, the organizational model for enforcement of such a scheme for used compact discs has existed in the United States for several generations. [17]

While we can argue that sales of used CDs constitutes rental, the potential for unlimited downloads of digitized copyrighted material requires that we take measures to tag the content in such a matter as to differentiate between copies of media that otherwise are seemingly identical. *However, if the means for tagging the content, a digital watermark, is easily overencoded with other information, a second digital watermark, in a manner which is impossible to independently verify, digital watermarking technology will not be able to serve any useful purpose to rights holders.* We call this "lack of invariance". The reasoning is that absent copyright registration, it will be impossible to successfully use the digital watermark *alone* to determine who has priority over the original work. Extensions that for a digital watermark the content *and* the embedded information are valuable to the determination of responsibility for the copy. The necessity of digital watermarking becomes questionable if the watermark message is easily overencoded or changed in a manner that cannot

provide for authentication. We believe the answer to authentication and nonrepudiation of digital watermarking are as important as the actual digital signalling process for embedding information into a media signal. How we accomplish such a *provably secure watermark* is the topic we address next, that of cryptographic integrity.

Money trail Rights holders seek to maximize recognition to realize commercial sales of artistic expression by the creator of the original work. However, copyright law requires that others must not be restricted from derivative works creation in the interest of advancing society's art and science.

Digital watermark requirements Copyright provides the copyright holder with protection over original expression but does not extend to preventing subsequent manipulation or "fair use" of said expression. The watermark system should thus focus on responsibility of the actual transacted copy, as bounded by "original expression", and should not restrict subsequent manipulation of the content.

Cryptographic Protocols: "Needles in a Haystack" Not Enough

While digital watermarks may be viewed as a form of embedded signalling, when applied to digitized samples of copyrighted media such as images, music and video, the more appropriate designation from a security standpoint is "steganography". Steganography, "[to] conceal the very existence of the message" [60], can easily be differentiated from cryptography, which "do[es] not conceal the presence of a secret message but render [s] [the message] unintelligible to outsiders by various transformations of the plaintext ('the message that will be put into secret form')" [60]. We detailed at some length methods available for digitizing analog media signals, and the dependence on processes enabling subsequent manipulation of the digitized representations of the original analog content. As for security, the availability of software and

hardware tools to sample signals and subsequently manipulate features in frequency, time, space and amplitude, are issues singled out as real threats to the security of any digital watermark. The linearity of digital signal processing (DSP), and related de emphasis on invariance, is rightly a topic of considerable concern to those seeking digital watermarking solutions to copyright infringement.

These concerns are understood but frequently ignored to the detriment of creators of content, who *expect* digital watermarking to provide a technical means for establishing responsibility over copies of their works. Most of the early on digital watermarking focused entirely on the actual watermark encode/decode process. The reasoning behind security concerns is the availability of decoders which provide any individual with a means to detect the embedded watermark, while failing to prevent such detection from leading to erasure or obscuring of the supposedly secure watermark message. *In this paper, we do not seek to prevent consumers from making choices over the technologies they chose to use, we do seek to debunk hype from fact in determinations made about how secure a digital watermark technology can be made.*

Some historical perspective will help in this discussion. What is steganography in actual application? We can use an example recorded in Greek history offering a simple characterization of the concept:

> Herodotus tells how another revolt- this one against the Persians- was set in motion by one of the most bizarre means of secret communication ever recorded. One Histiaeus, wanting to send word from the Persian court to his son-in-law,

> the tyrant Aristagoras of Miletus, shaved the head of a trusted slave, tattooed the secret message thereon, waited for a new head of hair to grow, then sent him off to his son-in-law with the instruction to shave the slave's head. When Aristagoras had done so, he read on the slave's scalp the message that urged him to revolt against Persia. [60]

An interesting story and instructive of the design requirements we seek with digital watermarking if the context of the technology and its limits are correctly applied.

First, we concern ourselves solely with hiding information within a signal in such a manner that we can recover it, with minimal error. If we expect high error it will be difficult to rely on the usefulness of the watermark message to make determinations of ownership. Second, unlike the poor slave depicted, we must assume that all potential pirates will attempt to obscure or erase the embedded watermark message as a means to subsequently pirate the content. In the case of the slave, the communication is highly important but restricted to a few individuals who are "in the know" and relates to the activity of war; in the case of copyrights, the communication of ownership over the original work is not a secretive activity if rights owners seek to exploit the potential value of the content.

We do not focus only on identification of content, especially of well-known works, as recognition assures the rights holder that consumers "know" the *Mona Lisa* or *Let it Be*. Commercially valuable content tends to have higher recognition. Similarly, it is probably not important to tattoo our own names for reasons of identification, although some do for other purposes! We can also

observe the more obvious tagging of physical goods in order to authenticate and otherwise control distribution of the good. This form of security is applied to currencies, clothing, compact discs, and other valuable commodities. Tagging items in retail stores provides a measure of protection against localized theft, especially if the tag is designed to destroy the good it is attached to after being triggered by some unauthorized event— taking clothing from the physical confines of a retail location.

We discussed the limits for similar destruction of media products, which may be downloaded to a consumers' PC, identifying the legal concept of fair use. If we cannot be assured that *every* consumer will subsequently redistribute the downloaded content, an act of piracy, we may be unfairly restricting consumers' rights. We can rightly assume that not *every* consumer is likely to engage in piracy in much the same manner we do not expect that *every* consumer is likely to create a derivative work from which they would like to subsequently exploit. This gray area leaves rights holders with the unfortunate choice of distributing their digitized copyrighted material with the inherent risk of subsequent piracy. If copyright owners can implement a means for digitally watermarking their content in such a manner that third parties may be able to authenticate the content, it is possible to provide for a digital equivalent to registration of copyrights.

Failure to implement such a system does not inherently effect the rights holder in terms of protection offered under the law, it does provide for a more efficient means for assuring consumers, distributors, or aggregators of content that they are trading in authentic media. In a perfect world, only watermarked content would be made available to consumers when in digital form. These

watermarked media goods and the complementary watermarking key, would constitute proof of ownership. The original unwatermarked content would continue to be out of reach to all but the rights holders. Solutions have been proposed by a number of companies which act as the arbiter of the priority of the digitized work, but the flawed nature of the registration is now better understood and has been the subject of research, some of which is available on the Internet [3, 4, 61, 62, 63] .

By understanding the nature of digital signal processing operations, we necessarily have a natural limit preventing absolute protection of any digital watermark message. Although the time value of the content can be estimated, providing a relevant window of opportunity for more detrimental piracy, rights holders seeking better protection need to consider digital watermarking techniques which combine both embedded signalling and cryptographic protocols designed to authenticate. Some theoretical descriptions of such techniques are beginning to be addressed by researchers who have started to analyze the limits of information hiding [64, 65, 66]. A designation for these approaches is "Public Key Steganography". Indeed, some early digital watermark researchers have also begun to implement cryptographic protocols in combinations with their embedded signalling algorithms [67]. From our earlier discussion, it is clear that much of the content currently being protected has value that is arguably less than the cost of purchasing digital watermark security [68]; however, the higher the potential value, the greater the need for provable security.

Unfortunately, the nascent digital watermarking "industry" has yet to endorse open and active testing of the many competing products that have been

introduced to the marketplace. Failure to properly test these products is not a problem in and of itself, it simply does not incorporate the lessons of the cryptography community who actively seek attacks on algorithms to better identify the time and cost trade-offs of given security products. *Ultimately, there is no such thing as perfect security, there is however plenty of evidence which supports contentions that many digital watermarking implementations are relatively "easy" to obscure or erase.*

Moreover, we cannot expect security by obscurity: believing that would-be pirates are not as smart as we are. For those interested in the methods for benchmarking digital watermarks, the web sites incorporated as references in this paper are informative. Patents for combining cryptographic protocols with embedded signalling have been issued and also provide additional perspectives on the requirement for provable security [8, 9, 12]. We also list a number of related embedded signalling patents, which do not include cryptographic protocols for authentication beyond the use of randomness in the encoding process [69 - 76]. Research in the area similarly indicates a serious lapse in understanding the inherent need for third part authentication as well as invariance. The many various watermarking processes described fail to enable a copyright holder to authenticate content that is subsequently overencoded using the same or other watermark processes [77 - 95].

Additional intellectual property has yet to be published by the US Patent & Trademark Office and concerns techniques for digital watermarking of software, among other advances in the technology [10, 11]. For purposes of highlighting the security we envision, we turn to the area of cryptography.

Shannon and his inadvertent lessons

Having argued there is no such thing as perfect security, there is a theory of perfect secrecy. The theory has its basis in the influential work of Claude Shannon. *A Mathematical Theory of Communication* and *Communication Theory of Secrecy Systems* resulted in the development of information theory as well as an understanding of cryptology in information theory terms [60]. The insight that "'In ... the majority of ciphers ... it is only the existence of redundancy in the original messages that makes a solution possible.' ... [M]ade possible, for the first time, a fundamental understanding of the process of cryptogram solution" [60].

Moreover, as relates to digital watermarking, Shannon observed:

> "'From the point of view of the cryptanalyst ... a secrecy system is almost identical with a noisy communication system.' In information theory, the term 'noise' has a special meaning. Noise is any unpredictable disturbance that creates transmission errors in any channel of communication. Examples are static on the radio, 'snow' on a television screen, misprints, background chatter at a cocktail party, fog, a bad connection on the telephone, a foreign accent, perhaps even mental preconceptions. ... 'The chief differences in the two cases,' he wrote, 'are: first, that the operation of the enciphering transformation is generally of a more complex nature than the perturbing noise in the channel; and, second, the key for a secrecy system is usually chosen from a finite set of possibilities while the noise in a channel is more often continually introduced, in effect chosen from an infinite set'" [60].

Why this is important regards the design goal of seeking to prevent unauthorized attempts at erasing a digital watermark by using naturally occurring noise, which is random, as a cover for the watermark data, which is not random. Shannon's description is helpful in the sense that in securing events, which may have time limits, the noise itself is random. The problem of taking this description too literally is that copyrighted media, which may generate a large number of copies, for instance a successful compact disc, the noise elements, can be isolated for analysis and manipulation. Various forms of collusion are possible with a number of watermarked copies of the content. This means a digital watermark cannot expect to be secure only by virtue of its hidden location within the digital media to be sold.

Some have described the signal-to-noise ratio (and measure of analog noise) and signal-to-error ratio (a measure of noise in a digitized representation of an analog signal) as important benchmarks for invisibly digital watermarking [96]. The practical reason is that because there is naturally-occurring noise, which is inherently random, and *always* resides in signals, we are able to imperceptibly encode data representing copyright, or any other information, in a manner which does not impact the *quality* of the copyrighted material. Still, the logic must be extended further in order to ensure that it is computationally costly or time-consuming to defeat the means for tagging the content. Simply overencoding certain parts of the signal with other random noise is not difficult and presents a fundamental weakness in the security of the watermark message. For ensuring detectability of such inadvertent or intended attempts at erasure, we need one-way functions.

A one-way function is intrinsically important for secure implementations of digital watermarking techniques. For, if we can only be assured that the embedded data is hidden, but susceptible to later tampering, security has not been provided. This is of paramount concern because of the advances in digital signal processing (DSP) discussed earlier. Theoretically, any consumer has access to inexpensive software and hardware tools, including any number of media file conversion and compression programs that allow for extremely precise manipulations of a copyrighted media work in digital form. What was previously thought to be an impossible activity, is, in actuality, relatively easy with minimal effort by parties familiar with DSPs [3, 4, 61, 62, 63]. Compression itself, both lossy and lossless, is a common starting point for testing how secure a watermark message is; but it is only a more generalized technology demonstrating the ability of individuals to process signals in such a manner, inadvertent or otherwise, which makes the concept of digital watermarking more complex than previously regarded [3, 4, 61, 62, 63, 67].

One-way functions for invariance

The basis for a perfect encryption scheme is more commonly designated a "one-time pad". Originally, "... a one-time pad [was] nothing more than a large nonrepeating set of truly random key letters, written on sheets of paper, and glued together in a pad. In its original form, it was a one-time tape for teletypewriters. The sender uses each key letter on the pad to encrypt exactly one plaintext character. ... Each key letter is used exactly once, for only one message. ... Since every plaintext message is equally possible there is no way for the cryptanalyst to determine which plaintext message is the correct one. ... If you use a real random source ... it's secure. ... Many Soviet spy messages to

agents were encrypted using one-time pads. These messages are still secure today and will remain that way forever" [97].

Although we simplify the matter of randomness, we also must point out that one-time pads cannot authenticate [97]. However, one-way functions can. These functions provide the fundamental basis for public key cryptography [97], precisely because we can theorize about the relationship between mathematical functions which are easy to compute but computationally complex to reverse. When cryptographers speak of "complexity" they measure the security of encrypted ciphertext data in terms the millions of years it would take using mind-boggling arrays of existing computers directed at determining the plaintext data. Suffice it to say many attacks exist to reduce the time for determining the sensitive plaintext data and the threat of simply stealing the keys used for encrypting the data remains, as these keys are susceptible to theft.

Another interesting example for simplifying why a digital watermark technology should incorporate the authenticating and nonlinearizing aspects of cryptography:

> So, what good are one-way functions? We can't use them for encryption as is. A message encrypted with the one-way function isn't useful; no one could decrypt it. (Exercise: Write a message on a plate, smash the plate into tiny bits, and then give the bits to a friend. Ask your friend to read the message. Observe how impressed he is with the one-way function.) For public-key cryptography we need something else. ... A trapdoor one-way function is a special type of one-

> way function, one with a secret trapdoor. It is easy to compute in one direction and hard to compute in the other direction. [97]

Of the protocols necessary to public-key cryptography, the one-way hash function provides cryptographers, and those seeking the security of cryptography, an efficient means for ensuring that the encrypted message cannot be altered without the knowledge of the party first encrypting the message. It is a bit more complicated than our simple generalization as there are protocols for symmetric cryptography, the same key is used to encrypt and decrypt a message; public-key cryptography, a private and public key pair are used for encryption where the private key is always kept secret; digital signatures, based on tree structure where the "root signs one message and authenticates its sub-nodes in the tree" [97]; time-stamping with secure clocks; and combinations of these processes to meet the security needs of a wide range of applications.

For simplicity we also note that public-key cryptography addresses issues of transmission security. While asymmetric systems provide this functionality they are generally slower than symmetric systems. For digital watermarking, we believe that, as with cryptography, combinations of public-key and symmetric key systems can be tailored to specific applications. It is believed by some that consumers should be able to authenticate content with digital watermarks, we are unsure this is necessary for all applications. Consumers similarly do not have access to original masters nor do they "own" the original expression, the ownership of a copyrighted material extends to an incarnation of ideas, e.g. the song or language, expressed by the creator. The copyright is simply the literal right to make a copy. For the consumer, the original expression is not being

transferred. However, our design allows for either type of implementation. A simple example is that the symmetric digital watermarking keys may also be transmitted using public-key cryptography.

For our purposes, we can design a watermarking algorithm which is able to define a signal in DSP terms, mask sets of the primary, or frequency, and convolution, or time or spatial, domains, where the actual encoding of the message is saved as a large random number corresponding the locations of the watermark message in the signal. This allows us to utilize the large random number, a "key", to encode and encode information into a target media signal. Many other digital watermarking systems chose a domain to encode in, either frequency or space, and stop at this point, incorrectly assuming the "key" alone is sufficiently secure. It does not guarantee others will not be able to successfully determine the random location, as we discussed previously, nor does it guarantee that others will not take the same or similar encoding process to embed *their* own information, confusing the issue of priority and ownership of the work! We believe encoding that uses both domains, as well as one-way functions applied to both the watermark message and encoding process are fundamentally invaluable for reliable digital watermark security.

It is this single distinction which makes digital watermarking a problem for cryptography as much as it is is a problem for DSPs. We know we do not want to affect the quality of the signal, that is what consumers seek to purchase, we also know we need to encode at a level which is easily confused with the signal's "noisy channel". However, in order for us to establish responsibility over the copy of the digitized signal, we must incorporate more than a simple random number, a so-called random seed, in the encoding process.

Incorporation of a one-way hash function, digital signatures, time stamps, are all dependent on how we randomly encode the watermark message. Using mask sets, which can theoretically represent any means for processing the signal, including compression [96], we must also hash the message itself as well as the message delimiters, which separate each instance, or copy, of a watermark message to be encoded into the signal. In doing this, we can be assured that the subsequently watermarked signal and its complement watermarking key, or key pair, can be used to establish priority over the original work. If the watermark message is encrypted, further security can be assured.

If we seek extremely high tamperproofing, saving a secure one-way hash or digital signature of the actual watermark message on the watermarking key, will allow us to detect the tampering of a single bit of the watermarked content, inadvertent or not. Perhaps this level of security is the requirement of a future when digital distribution is a valuable commercial industry. For the present, we need to establish recognition that tampering with the watermarked signal will likely result in an authentication check failure, the beginnings of third party authentication and accurate monitoring of digitized copyrighted content.

Tamperproofing watermarked content with cryptography

We have discussed a number of inter-related issues concerning convergence and its likely impact on decisions copyright holders will likely need to consider. Of the topics thus far, none is more central to convergence than the issue of cryptographic protocol as applied to digital watermarking. Digital watermarking offers a large number of promising means for invisibly or inaudibly hiding information in the media signals the watermark messages are intended to identify. While work in digital signal processing (DSP) is entirely subjective, the

boundaries of time and cost of computation are as relevant as the time and cost considerations made for cryptography implementations.

The fundamental difference is the tolerance of error in DSP operations, when factoring in natural signal-to-noise and, its digital equivalent, signal-to-error, is far greater than error acceptable in the strict mathematical confines of cryptography. If cryptography had error rates approaching those expected in DSP work, little if any security benefit would be evident in most implementations. One percent error for an ATM machine in correctly accepting a consumers' secret code, would result in a huge increase in inconvenience to consumers and the customer services representatives hired to assist them! We believe digital watermarks must also demonstrate extremely high error-free use in order to be of dependable commercial use to copyright holders and the serious battle against piracy.

In the legal section of this paper, we described the prudent activity of registering and enforcing copyrights, to ensure uncompensated use can be measured in later determination for subsequent action against infringers. We also discussed the threat of entertainment overload and the fragmentation of the number of physical and nonphysical channels in which to reach consumers. We also covered the concept of fair use, as a limiting factor on how much protection is legally possible, within a very debatable space of potential restrictions that may be levied against those seeking protection from unauthorized use of copyrighted media works. The number of digital watermark attacks, based on DSP operations, described has not yet entered into the realm of cryptographic attacks. It is possible that cryptographic attacks are on the horizon, but too

many of the presently available digital watermarking products must first demonstrate DSP bounded survival [3, 4, 61].

We believe that the inherent ease with which to search for digital watermark locations within a signal makes technology designed to search the Internet for watermarked content, a curious offering. That many sites are not accessible to such "web-crawlers" is one obvious weakness [68], that the same algorithm used to check the watermark can also be used for successfully erasing the watermark is of far greater concern. Beyond issues of time value of content, where the time it takes to automatically search the "entire" Internet, though not those sites that are protected, presently takes an estimated two months, it is likely that the watermarked content, if and when it is discovered, may have already been rendered worthless [13, 19, 21, 22, 68]. *We do not detract from the effort just identify if the commercial value provided by such services can be correctly determined.*

Under the paradigm, existent in physical goods distribution, that vendors should authenticate the copyrighted, or trademarked, goods they may commercially exploit, it is hard to find reason this responsibility should not extend into the digital domain. Certainly active enforcement and monitoring of unauthorized downloading of content and resulting efforts at legal action will assist in educating consumers, but at an admittedly high price. We do believe the cost of the activity is justified, given the unpredictable nature of just how digital distribution will affect copyright owners. A similar means for third party authentication of on-line media can only happen if all parties agree to designate an authentication authority, or endorse a common technology making third party authentication possible by others. The example of trusted authorities in

cryptography is not lost on this belief [97]. In fact, the ability to create watermarking keys, which both encode and decode, or watermarking key pairs, which encode and decode using public/private-key pairs, which may be authenticated, is central to the success of a market for exchanging digitized content.

Some additional observations may be made with regards to the size of the watermarking key as it relates to the more familiar concept of cryptographic keys. As long as the watermark key is smaller in data size, and larger than the watermark message, than the content to be watermarked, there is an efficient means for authenticating or digitally registering copyrights. We know that "... if the total length of the [message] is greater than the length of the private key then, no what encryption system is used, Eve [the eavesdropper] provably has some information about the content of the messages from the encryptions sent on the public line" [98]. In digital watermarking, we already know that the shear number of copies of the content sought to be distributed and sold is necessarily a means for pirates to make comparisons of copies and attempt to independently or collusively erase the embedded watermark. The time value of the content is on the side of the copyright holder vis-a-vis the pirate, but this cannot be expected over the long term, and secure one-way hash functions or digital signatures of both the embedded message and its encoding path, the message delimiter, provide some relief, to the problem. Similarly:

> ... Eve may not have enough computational resources (e.g., time) to be able to compute any revealing information about the content of the sent message. The idea is to exploit the computational limitations of Eve. Intuitively, what Alice and Bob want to do is to encrypt very long messages using a short random

> private key in such a way that the encryptions are indistinguishable from truly random noise to any eavesdropper with reasonable computational limits. At the heart of the encryption system we use to implement these ideas is a pseudorandom generator. [98]

While this indicates we must use suitably random numbers for safely encoding information into a signal, we again must not ignore the inherent weakness ascribed to simple noisy channel encoding, or so-called subliminal channels.

So long as the message can be embedded in such a manner that attempts at removal, inadvertent or not, can be detected, we can be assured of future implementations of security which are provably secure, as we also can observe in applications in the real world, under the similar condition that we expect many unknown parties to have access to the watermarked content, and thus the embedded signal. "Other [subliminal channel] applications are more subtle. A company can [digitally] sign documents and embed subliminal messages, allowing them to be tracked throughout the documents' lifespans. The government can 'mark' digital cash. ... The possibilities are endless" [97].

In further cross application of cryptographic protocols, an undeniable cryptographic watermarking key can be envisioned: "... [A]n undeniable signature depends on the signed document [for watermarking, the watermark message] and the signer's private key [i.e., the copyright holder's private watermark key]. But, unlike normal digital signatures, an undeniable signature cannot be verified without the signer's consent [i.e., copyright holders consent to distributor's of copyrighted content]" [97]. The protocol can be extended to authorized third parties who may be entrusted to verify the signature, protecting

the identity of the signer, or simply effectuating more widespread authentication as is evident in secure, authenticatable credit card processing.

There are certainly a wide range of additional sources of interest to readers seeking a better understanding in the related fields we feel are necessary in considerations made for a secure, workable framework for digital watermark applications.

Money trail Digital watermarking companies offer security as a form of insurance. Other digital watermarking companies simply seek to affix themselves within the distribution channel.

Digital watermark requirements The inexact nature of digital signal processing has little relationship to the more demanding requirements of relatively error-free cryptographic security. Because digital watermarks can never be assumed to be permanently hidden or secure from inadvertent processing or unscrupulous parties, authentication and tamperproofing can be assured by incorporating one-way functions to the embedded signalling process. It is also important to seek more consistent authentication activities by distributors to assure that only authorized content is distributed. Depending on the media to be watermarked and the means for distribution, symmetric or asymmetric keys may be used alone, or in combination. The issue of transmission security as well as computational efficiency will likely determine which cryptographic protocols are commercially acceptable.

Digital Watermarks: A Philosophical View

We have covered a range of subjects with varying impacts on the technology of digital watermarking. What is still missing is some short observations on how art and mathematics relate to the human concept of value. Pythagoras established the first school of proof in an effort to determine the underlying recipes of observable phenomenon; efforts which resulted in the first linkages

between science and math, as we define these concepts in the modern age [99]. His school was not the first to seek answers evident by mysterious in the performances of musicians. But, "Pythagoras had discovered that simple numerical ratios were responsible for harmony in music" [99].

The obvious question is: why does art evoke feelings in humans? Many advances in mathematics came from observations of music and attempts at characterizing physical phenomenon commonly observed in musical instruments. It was a Viennese composer who went further in analyzing related human feelings or, conversely, messages that may be contained in the music.

> Around 1910, a Viennese composer named Arnold Schoenberg decided that, since he could see no obvious answer to the problem of why music touches our feelings, the answer must lie in the word 'habit'- or conditioning. Schoenberg decided that he would create a different tone scale, and write music that was based on a number of notes arranged in arbitrarily chosen order- rather than one that 'appeals' to the ear. But he proved mistaken in his assumption that music is 'arbitrary'. Almost a century later, his works and those of his disciples still sound strange and dissonant- and their inclusion in a modern concert programme is enough to guarantee a decline in ticket sales. Any Pythagorean could have told him that his theory was based on fallacy- a failure to grasp that there is a hidden mathematical reason why a certain order of notes strikes us as harmonious, and why arbitrary notes fail to convey a sense of musical meaning. [100]

This explains some of the philosophical reason we seek media which entertains us, but hard and fast rules for creativity are impossible to characterize by

mathematical rules alone. Harder still, math cannot guarantee successful commercial exploitation.

Other artists had the genius of composing more highly complex music that is arguably breathtaking. How do we characterize the feelings evoked? Perhaps "... form, in music, is expressive— expressive to some strange subconscious regions of our minds. ... [M]usical meaning *is* dependent on intangible links from the symbols to things in the world- those 'things', in this case, being secret software structures in our minds. No, great music will not come out of ... easy formalism ... " [101].

We can explore further links between creative processes and the appeal of the structured artistic work with our senses. "Visual art, music, mathematics, mantra, numbers, and form are all investigations of structure. They aim to discover structures that reflect the fundamental structures of the cosmos. But there may also be a mystical purpose, such as the objective of attaining a state of higher consciousness through this process of discovery. In the latter case, the goal of the investigation isn't the discovery of the structures themselves" [102]. An interesting abstraction of art. Shinichi Suzuki, pioneer of the Suzuki method of studying violin was more adamant: "'Teaching music is not my main purpose ... I want to make good citizens, noble human beings. If a child hears fine music, and learns to play it himself, he develops sensitivity, discipline and endurance. He gets a beautiful heart'" [103].

With music we can associate memories. With visual art we can be similarly, emotionally moved. "... [S]ymbols ... can evoke a richer, more complex reality inside us. Great music and poetry produce the same effect" [100]. If digitization

of media is the process of successfully representing typically analog media signals, we have enabled ourselves to project the act of creative discovery to a far greater number of people than has ever been possible. Violin instructor Suzuki: "'Perhaps it is music that will save the world'" [103].

While we have innate feelings about artistic expression, or the concept of original work as defined in legal terms, we can characterize the perceptually significant features of any given digitized signal as being the salient features of the work. In lossy compression, for instance, listening to music over an AM-quality station, we are still able to associate with a facsimile of the art that evokes human feeling. If further degradation prevents this association, the representative work no longer has any appeal.

Why does the creator create? An interesting quote from an uniquely titled book, *A Mathematician's Apology*, is applicable to any artist regardless of any subsequent commercial exploitation of their work *(emphasis added)*:

> I will only say that if a chess problem is, in the crude sense, 'useless', then that is equally true of most of the best mathematics ... I have never done anything 'useful'. No discovery of mine has made, or is likely to make, directly or indirectly, for good or ill, the least difference to the amenity of the world. Judged by all practical standards, the value of my mathematical life is nil; and outside mathematics it is trivial anyhow. **I have just one chance of escaping a verdict of complete triviality, that I may be judged to have created something worth creating. And that I have created something is undeniable: the question is about value.** [99]

*It may be that those same "**perceptually significant**" features, which can be mathematically described with digital signal processing, are, in fact, the key component parts, the value inherent to the **actual original expression** that must be tagged by a secure digital watermarking process to enable a l**asting , undeniable association** with the creator of the work.*

A Theory for Secure Digital Watermarking

- The time and cost of digital watermarking security should not exceed the projected value of the content to be protected

- It must be possible to authenticate a watermark message with only the watermarked content and the watermarking key, or key pair.

- False positive results for a given watermark message and the watermarking key, or key pair, must meet cryptographic standards of error

- Authentication, or failure to authenticate, of the watermark message must survive subsequent encoding with the same or other watermarking processes

- Digital watermark message survival, although subjective, must extend to the limits bounded by "fair use"

- A digital watermarking system should be implementable by an individual content creator, where authentication of the watermarked content is possible by third parties

- In digitized form, content should only be distributed with watermarks if the watermarks are expected to provide authentication or tamperproofing

Appendix
More Technical Details: Nyquist and Quantization

The sampling theorem, and that known specifically as the Nyquist Theorem, proves that bandlimited signals can be sampled, stored, processed, transmitted, reconstructed, desampled or processed as discrete values. In order for the theorem to hold, the sampling must be done at a frequency that is twice the frequency of the highest signal frequency one seeks to capture and reproduce. Aliasing will occur as a form of signal foldover, if the signal contains components above the Nyquist frequency. To establish the highest possible quality in a digital signal, aliasing is prevented by low-pass filtering the input signal to a given digitization system by means of lowpass or anti-aliasing filter. Any residue aliasing which may result in signal distortion, relates to the next area of signal quality control, quantization error removal.

Quantization is required in a digitization system. Because of the continuous nature of an analog signal (amplitude vs. time), when it is sampled, its quantization is an imperfect estimate of the signal sample, in order to encode it as a series of integral numbers. These numbers are merely estimates of the true value of the signal amplitude. Where there is a difference between an actual analog value at a discrete time and the quantization value-- quantization error occurs. The more bits allowed per sample, the greater the accuracy of estimation, but error will always occur. It is the recurrent nature of this type of error that provides an analogy with the location of digital watermarks. Thus, methods for removal of such errors have relevance in methods for determining the most secure locations for said watermarks, if one hopes to prevent the removal of such watermarks. Best case for an engineer seeking high fidelity in digital reproduction of a signal is at points where the analog signal converges with a given quantization interval. Where there is no such convergence, in varying degrees, the quantization error will be represented by the following range:

+Q(quantization interval)/2 and -Q/2

Indeed, describing maximization of the quantization error and its ratio with the maximum signal amplitude, as measured, will yield the signal-to-error ratio (S/E) closely related to analog signal-to-noise ratio (S/N). Error is random. Very welcome to those skilled in the art of inserting a digital watermark. To establish more precise boundaries for determining the S/E, with root mean square (rms) quantization error E_{rms} , and assuming a uniform probability density function 1/Q (amplitude), the following describes the error:

$$E_{rms}=Q/(12)^{1/2}$$

Signal to quantization error is expressed:

$$S/E=[S_{rms}/E_{rms}]^2=3/2(2^{2n})$$

Finally, in decibels (dB) and comparing 16-bit and 15-bit quantization:

$$S/E(dB)=10\log[3/2(2^{2n})]=20\log[(3/2)^{1/2}(2^n)]$$
$$=6.02n+1.76$$

This explains the S/E ratio of 98 dB for 16-bit and 92 dB for 15-bit quantization. Establishing, statistically, the 1.76 factor is a result of peak-to-rms ratio of a sinusoidal waveform but will differ if the signal differs from such waveforms. In complex audio signals, any distortion will exist as white noise across the audible range. Low amplitude signals may alternatively suffer from distortion.

Quantization distortion is directly related with the original signal and is thus contained in the output signal, they are not simply errors. This being the case, implementation of so-called quality control of the signal must use dither. Use of linear and nonlinear quantization can effect the trade-off in the output signal and must be considered for a system of watermarks designed to determine "acceptable" quantization distortion which would contain a digital

watermark. For audio systems, block linear quantization implementations have been chosen though block floating point and floating point systems, nonuniform companding, adaptive delta modulation, adaptive differential pulse-code modulation, and perceptual coding schemes (which are oriented around the design of filters that closely match the actual perception of humans) appear to provide alternative method implementations that would cause higher perceptible noise artifacts if subsequent filtering for watermarks was undertaken by pirates for given content signals-- the choice of method being related to the information overhead desired. It is still a valid contention that the envelope being described in the quantization equations above is suitable to preanalysis of a given digitized sample in evaluating optimal locations for watermarks. The example is for audio but corresponding applications for digitization of video would be apparent in the quantization of color frequencies.

The matter of dither complicates preanalysis of a given sample evaluated for digital watermarks. It also defines the optimal envelope more closely given the three types of dither (this example is for audio, others exist for video): triangular probability density function (pdf), Gaussian pdf, and rectangular pdf. Again, to establish better boundaries for the random, or pseudo random, insertion of a watermark to exist in a region of a content signal that would represent an area for hiding watermarks in a manner most likely to cause damage to the content signal if unauthorized searches or removal are undertaken. Dither makes removal of quantization error more economical through lower data overhead in a system by shifting the signal range to decorrelate errors from the underlying signal. When dither is used, the dither noise and signal are quantized together to randomize the error. Dither which is subtractive would require removing the dither signal after requantization and creates total error statistical independence. It would also provide further parameters for digital watermark insertion given the ultimate removal of the dither signal before finalizing the production of the content signal. With nonsubtractive dither the dither signal is actually permanently left in the content signal. Errors would not be independent between samples. For this reason, further analysis with the

three types of dither should reveal an acceptable dither signal without materially affecting the signal quality.

References

[1] K. Pohlmann. *Principles of Digital Audio*. McGraw Hill, 3rd edition, 1995.

[2] K. Castleman. *Digital Image Processing*. Prentice Hall, 1996.

[3] F. Petitcolas. *StirMark*, a watermark testing application as well as other discussion on still image watermark weaknesses available at the following:
http://www.cl.cam.ac.uk/~fapp2/watermarking/image_watermarking/stirmark/.

[4] F. Petitcolas. Attacks on Copyright Marking Systems. *Submitted to Second International Workshop in Information Hiding*. Portland, Oregon, April 1998. On the Internet at:
http://www.cl.cam.ac.uk/~fapp2/papers/ih98-attacks/

[5] D. Gruhl, A. Lu, & W. Bender. Echo Hiding. In Ross Anderson, editor, *Proceedings of the First International Workshop in Information Hiding*. Lecture Notes in Computer Science, pages 295-315, Cambridge, UK, May 30- June 1, 1996. Springer.

[6] *Private communications* with Dr. Peter Craven of Algol Applications, November 1996-March 1997.

[7] *Private communications* with John Monforte of the University of Miami/University of Michigan, April 1996-August 1997.

[8] M. Cooperman and S. Moskowitz. *Steganographic Method and Device*. US Patent #5,613,004, March 18,1997.

[9] S. Moskowitz and M. Cooperman. *Steganographic Method and Device*. US Patent #5,687,236, November 11,1997.

[10] S. Moskowitz and M. Cooperman. *Method for Stega-Cipher Protection of Computer Code*. US Patent. Yet to be published by the U.S. Patent & Trademark Office.

[11] S. Moskowitz and M. Cooperman. *Method for Stega-Cipher Protection of Computer Code*. US Patent. Yet to be published by the U.S. Patent & Trademark Office.

[12] S. Moskowitz and M. Cooperwman. *Method for Human-Assisted Random Key Generation and Application for Digital Watermark System*. US Patent. Yet to be published by the U.S. Patent & Trademark Office.

[13] *Private communications* with Universal/MCA, Olympus Software Europe, Sony, EastWest, Reuters, Alinari, ASCAP, BMI, RIAA, Time Warner, Netscape, Maverick Records, The Harry Fox Agency/NMPA, Thomas Dolby, Radio Computing Services, Criteria Studios based on demonstrations and testing of the Giovanni™ digital watermark system, the Argent™ digital watermark system, its predecessor implementation, and the Giovanni™ Scrambler/Player, 1995-1998.

[14] *Private communications* with TNO/Bakkenist engineers, conducting the audio industry embedded signalling testing, as well as publicly-available information by Solana Technology, ARIS Technologies, TDF, Mikros Systems, Arbitron, CRL and, BBN on their audio digital watermarking techniques as submitted to International Federation of the Phonographic Industry (IFPI)/MUSE Embedded Signalling Request For Proposals, April 1997-January, 1998.

[15] I. Cox, J. Killian, T. Leighton, and T. Shamoon. Secure Spread Spectrum Watermarking for Multimedia. In *NEC Research Institute, Technical Report 95 - 10*, 1995.

[16] P. Newcombe. *Forbes*. The music never stopped. Pages 90-95, March 24, 1997.

[17] C. Miller. *New Technology and Old Protection: The Case for Resale Royalties on the Retail Sale of Used CDs*. Hastings Law Journal, Volume 46, pages 217-241, November 1994.

[18] *Private Communication* with AmericDisc regarding cost of compact disc and cassette manufacturing for commercial distribution, April 1993.

[19] *Private communications* with Steve McClure of Billboard, 1992-1997.

[20] *Private communications* with Paul Jessop of International Federation of the Phonographic Industry (IFPI), 1996-1997.

[21] *Private communications* with Andrew Bassin, Jerry Bassin and Alan Tuchman of Alliance Entertainment (all, previously with Bassin Distributors), 1992-1998. Related to on-line efforts:

C. Lee. *The Wall Street Journal*. N2K Inc., On-line Music Retailer, Gets Mixed Review on Its Outlook. Page B5A, March 9,1998.

[22] *Private communications* with Jon Kabira of JWAVE, 1992-1998.

[23] E. Christman. *Billboard*. FTC Widens Inquiry Of Music Biz Practices. Page 9, October 11,1997.

[24] *The Economist*. In search of the perfect market. A Survey of Electronic Commerce, May 10,1997. Related but more critical of on-line retail efforts: C. Rosen. *Billboard*. CDnow Grammy Discount Draws Criticism. Page 3, March 7,1998.

[25] *Economist*. Surf Music. Pages 47-48, August 16,1997.

[26] D. Reece. *Billboard*. Music Retailers Criticize Label Sales On Internet. Pages 1, 108, October 4, 1997.

[27] D. Reece.*Billboard*. Web Sales Issue Bandied At Musicom. Pages 53, 70, November 29, 1997.

[28] H. Hovaness and D. D'Ordine. *Billboard*. Web-based Distribution Means Big Changes Ahead. Pages 6, 55, January 31, 1998.

[29] D. Jeffrey and E. Christman. *Billboard*. The State Of The Music Industry '98. Pages, 1, 96, February 14,1998.

[30] *Wired*. Quantum Pricing for Information. Page 63, August 1994.

[31] E. Dyson.*Wired*. Intellectual Value. Page 137, July, 1995.

[32] P. Ross. *Forbes*. Cops versus Robbers in cyberspace. Pages 134-139, September 9, 1996.

[33] D. Stoltz, M. Stoltz, and W. Earle. *The Advertising World of Norman Rockwell*. Madison Square, 1985.

[34] *Private communications* with Curtis Publishing regarding the commercial licensing of Norman Rockwell images, Summer 1994.

[35] *The Economist*. Most-wanted photography. Pages 85-86, February 7,1998.

[36] *The Economist*. At last, a people's art. Page 77, January 17, 1998.

[37] *Financial Times*. Winner takes all. Page 6, January 17, 1998.

[38] *The Economist*. Tackling monopolies. Page 80, February 7,1998.

[39] *The New York Times*. From Gurus to Sitting Ducks. Section 3, Page 1, 9, January 11, 1998.

[40] T. Barkow, ed. *Wired*. Raw data. Page 72, August, 1997.

[41] A. Arrate. *The Miami Herald*. Pirates steal a different kind of gold. Pages 1A, 22A, September 7,1997.

[42] R. Guzman. *The Wall Street Journal*. CDs, as Easy as MP3. Page A14, January 9,1998.

[43] P. Judge. *Business Week*. Are Tech Buyers Different? Pages 64-68, January 26,1998.

[44] S. Watts. *The Magic Kingdom: Walt Disney and the American Way of Life*. Houghton Mifflin, 1997.

[45] R. Brealey and S. Meyers. *Principles of Corporate Finance*. McGraw-Hill, 2nd edition, 1984.

[46] S. Davidson, C. Stickney & R. Weil. *Financial Accounting An Introduction to Concepts, Methods, and Uses*. Dryden, 4th edition, 1985.

[47] *The Economist*. Slipped disc. Page 60, January 3,1998.

[48] *The Economist*. In the picture. Page 67-68, January 10,1998.

[49] S. Goldstein. *Fox Jumps On Divx Train Studio Still A Holdout On Basic DVD*. Pages 10, 79, February 28,1998.

[50] A. Gove. *The Red Herring*. Divxing up the market. Pages 36-38, December 1997.

[51] *Billboard*. The Survey Says: What's DVD? Pages 69, 72, February 14,1998.

[52] *T. Carroll*. Frequently Asked Questions document on copyright law. Internet site: ftp://ftp.aimnet.com/pub/users/carroll/law/copyright/faq/part2

[53]*Lotus Development Corporation v. Borland International, Inc.*, 49 F.3d 807, 818 (1st Cir. 1995).

[54] P. Durdik. *Reverse Engineering As A Fair Use Defense To Software Copyright Infringement*. Jurimetrics Journal, 34, pages 451-470, Summer 1994.

[55] The Economist. *Economic Indicators*. Advertising, page 96, January 17,1998.

[56] E. Stevens and R. Grover. *Business Week* The Entertainment Glut. Pages 88-95, February 16,1998.

[57] *Press Release*. NMPA Views Landmark CompuServe Settlement Agreement As Precedent For All On-Line Computer Services. November 7,1995.

[58] J. Birbaum. *The New York Times.* Without a Scratch, Used CD's Rise Again, September 6,1993.

[59] E. Christman. *Billboard*. Both Retailer, Label Claims Backed Up by Used-CD Survey. Page 4, 112, October 2,1993.

[60] D. Kahn. *The Codebreakers*. Scribner, revised edition, 1996.

[61] S. Craver, N. Memon, B. Yeo, and M. Yeung. Can Invisible Watermarks Resolve Rightful Ownerships? In *IBM Research Report*, RC20509, July 25,1996.

[62] *UnZign*, a watermark testing application as well as other discussion on still image watermark weaknesses available at the following: http://www.altern.com/watermark/

[63] *Digimark Cracked*. A network-based attack on a commercial still image watermarking system described at (and elsewhere):
http://www.altern.com/watermark/51.html

[64] R. Anderson, editor. *Proceedings of the First International Workshop in Information Hiding*. Lecture Notes in Computer Science, Cambridge, UK, May 30- June 1, 1996. Springer.

[65] R. Anderson. *Stretching the Limits of Steganography*. http://www.cl.cam.ac.uk/ftp/users/rja14/steganjsac2., 1996.

[66] R. Anderson and F. Petitcolas. *On The Limits of Steganography*. http://www.cl.cam.ac.uk/ftp/users/rja14/stegan., 1997.

[67] J. J. K. 'O Ruanaidh and T. Pun. *Rotation, Scale and Translation Invariant Digital Image Watermarking*. Paper to be published, received Summer 1997.

[68] D. Isenberg. *Digital Watermarking*. Mecklermedia, revised on-line article (3 of 4 parts), January 26,1998.
http://webreference.internet.com/content/watermarks/overview.html
http://www.webreference.com/content/watermarks/interaction.html
http://www.webreference.com/content/watermarks/conclusion.html

[69] Preuss et al. *Embedded Signalling*. US Patent #5,319,735, June 7,1994. (assigned to Bolt, Beranek & Newman, Inc.)

[70] G. Rhoads. *Steganography Methods Employing Embedded Calibration Data*. US Patent #5,636,292, June 3,1997. (assigned to Digimarc Corp.)

[71] G. Rhoads. *Method and Apparatus Responsive to a Code Signal Conveyed Through a Graphic Image*. US Patent #5,710,834, January 20,1998. (assigned to Digimarc Corp.)

[72] Lee et al. *Post Compression Hidden Data Support*. US Patent #5,687,191, November 11,1997. (assigned to Solana Technology)

[73] Aijala et al. *Method and Apparatus for Encoding/Decoding Broadcast or recorded Segments and Monitoring Audience Exposure Thereto*. US Patent #5,579,124, Novemebr 26,1996. (assigned to Arbitron)

[74] Ellis et al. *Method and System for Producing a Signature Characterizing an Audio Broadcast Signal*. US Patent #5,612,729, March 18,1997. (assigned to Arbitron)

[75] Ellis et al. *Method and System for Recognition of Broadcast Segments*. US Patent #5,436,653, July 25,1995. (assigned to Arbitron)

[76] Ellis et al. *Method and System for Recognition of Broadcast Segments*. US Patent #5,621,454, April 15,1997. (assigned to Arbitron)

[77] W. Bender, D. Gruhl, N. Morimoto, and A. Lu. Techniques for data hiding. *IBM Systems Journal*, 35(3&4), pages 313-336, 1996.

[78] H. Berghel and L. O'Gorman. Protecting Ownership Rights through Digital Watermarking. *IEEE Computer*, 29(7), pages 101-103, 1996.

[79] H. Berghel. Watermarking Cyberspace. *Communications of the ACM*, 40(11), pages 19-24, November 1997.

[80] L. Boney, A. H. Tewfik, and K. N. Hamdy. Digital Watermarks for Audio Signals. *1996 IEEE Int. Conf. on Multimedia Computing and Systems*, pages 473-480, Hiroshima, Japan, 1996.

[81] A. Bors and I. Pitas. Embedding Parametric Digital Signatures in Images. *EUSIPCO-96*, volume III, pages 1701-1704, Trieste, Italy, September 1996.

[82] A. Bors and I. Pitas. Image Watermarking Using DCT Domain Constraints. *IEEE International Conference on Image Processing (ICIP'96)*, volume III, pages 231-234, Lausanne, Switzerland, September 1996.

[83] F. Hartung and B. Girod. Digital Watermarking of Raw and Compressed Video. *Proceedings of European EOS/SPIE Symposium on Advanced Imaging and Network Technologies*, Vol. 2952, pages 205-213, Berlin, Germany, October 1996.

[84] E. Koch and J. Zhao. Towards Robust and Hidden Image Copyright Labeling. *Proceedings of 1995 IEEE Workshop on Nonlinear Signal and Image Processing*, pages 452-455, Halkidiki, Greece, June 1995.

[85] J. J. K. 'O Ruanaidh et al. Watermarking Digital Images for Copyright Protection. *IEEE Proceedings*, Vol. 143, No. 4, pages 250-256, August 1996.

[86] I. Pitas and T. H. Kaskalis. Applying Signatures on Digital Images. *IEEE Workshop on Nonlinear Image and Signal Processing*, pages 460-463, Neos Marmaras, Greece, June 1995.

[87] I. Pitas. A Method for Signature Casting on Digital Images. *IEEE International Conference on Image Processing (ICIP'96)*, volume III, pages 215-218, Lausanne, Switzerland, September 1996.

[88] J. Puate and F. Jordan. Using Fractal Compression Scheme to Embed a Digital Signature into an Image. *Proceedings of SPIE'96*, Vol. 2915, 3/97, pages 108-118, Boston, Massachusetts, 1996.

[89] R.G. van Schyndel, A.Z. Tirkel, and C.F. Osborne. A Digital Watermark. *IEEE International Computer Processing Conference*, pages 86-90, Austin, Texas, November 13-16,1994.

[90] R.G. van Schyndel et al. Towards a Robust Digital Watermark. *Second Asian Image Processing Conference*, volume 2, pages 504-508, Singapore, December 6-8, 1995.

[91] M. D. Swanson, B. Zhu, and A. H. Tewfik. Robust Data Hiding for Images. *7th IEEE Digital Signal Processing Workshop*, pages 37-40, 1996.

[92] M. D. Swanson, B. Zhu, and A. H. Tewfik. Transparent Robust Image Watermarking. *1996 SPIE Conf. on Visual Communications and Image Processing*, volume III, pages 211-214, 1996.

[93] A. Z. Tirkel et al. A Two-Dimensional Digital Watermark. *DICTA '95*, 7 pages, University of Queensland, Brisbane, December 5-8, 1995.

[94] A. Z. Tirkel et al. Image Watermarking: A Spread-Spectrum Approach. *ISSSTA '96*, 6 pages, Mainz, Germany, September 1996.

[95] M. M. Yeung, F. C. Mintzer, G. W. Braudaway, and A.R. Rao. Digital Watermarking for High-Quality Imaging. *Technical Report RC20797,* IBM T.J. Watson Research Center, 1997.

[96] J. Smith and B. Comiskey. Modulation and Information Hiding in Images. In Ross Anderson, editor, *Proceedings of the First International Workshop in Information Hiding*. Lecture Notes in Computer Science, pages 207-226, Cambridge, UK, May 30- June 1, 1996. Springer.

[97] B. Schneier. *Applied Cryptography*. Wiley, 2nd edition, 1995.

[98] M. Luby. *Pseudorandomness and Cryptographic Applications*. Princeton, 1996.

[99] S. Singh. *Fermat's Last Theorem*. Fourth Estate, 1997.

[100] C. Wilson. *From Atlantis to the Sphinx*. Virgin, 1997.

[101] D. Hofstadter. *Godel, Escher, Bach: An Eternal Golden Braid*. Vintage, 1989.

[102] S. Holtzman. *Digital Mantras: The Languages of Abstract and Virtual Worlds*. MIT, 1994.

[103] *The Economist*. Obituary. Shinichi Suzuki. Page 90, February 7,1998.

Additional Background References of Particular Interest

1994 3DO company reports and 10K.

"Adobe Gets Lift in Bid to Set Standard For Sending Documents Over Internet" The Wall Street Journal, March 28,1995, p. B6.

"All Music" Wired, February 1994, p. 52.

"American cable television Not now, darling" The Economist, September 3,1994, p. 63.

"American Gladiators AT&T and MCI Face Off" Wired, May 1994, p. 137.

"America's sorcerer" The Economist, January 10,1998, p. 71.

"Apple-IBM Goal of Universal Computer Faces Hurdles" The Wall Street Journal, October 9,1994.

"Are Corporate Predators On The Loose?" Business Week, February 23,1998, pp. 124-126.

"Are Patents and Copyrights Morally Justified?" Harvard Journal of Law and Public Policy, vol. 13, 1989, pp. 817-865.

"ARM's race" The Economist, September 27,1997, p. 67.

"The art of our time" Forbes, December 29,1997, p. 108.

"The Artist Makes Waves At Retail With 'Ball' Set" Billboard, March 7,1998, pp. 50, 52.

"AT&T Scraps Plan to Sell Gear For Video Game" The Wall Street Journal, September 1,1994, p. B10.

"Attention Shoppers!" Wired, December 1997, pp. 182-190.

"Audio Sweet Sounds On the Web" Business Week, February 16,1998, p. 121.

"Barbarella Unplugged" The Red Herring, December 1997, p. 25.

"Barry Diller's next course" Forbes, March 9,1998, pp.122-124.

"The Best Job in the World" Forbes, March 28,1994, p. 51.

"Better than the real thing" The Economist, January 24,1998, p. 65.

"The bg sqz" The Economist, January 15,1994, p. 88.

"Booting electronic books" The Economist, September 3,1994, p. 83.

"'Bridget' and Other Small Rock Bands Move Recording From Studio to Garage" The Wall Street Journal, July 12,1995, p. B1.

"Buy Cycles Users of Internet/Online Services" Billboard, March 7,1998, pp. 48, 52.

"Cable's hold on America" The Economist, January 24,1998, p. 61.

"CamNet: Those Who Cam, Do" Wired, September 1994, p. 74.

"Can pay, won't pay" The Economist, February 14,1998, p. 13.

"Can Pixar Keep Up The Magic?" Business Week, February 16,1997, p. 115.

"Capitol Records Plans to Use Internet For Sales of a Pop Single Via Modem" The Wall Street Journal, September 5,1997, p. B6.

"CD-ROM Based 3DO Struggles In Video Game Marketplace" St. Petersburg Times, August 8,1994, p. 4D.

"CES Provides Music To Ears Of Audio Industry" Billboard, January 7,1995, p. 89.

"The Christmas videogame massacre" The Economist, November 19,1994, p. 73.

"A Classic Problem" The Economist, October 19, 1996, p. 113.

"Compact discs Cheap at any price?" The Economist, May 7,1994, p. 66.

"The Computer for the 21st Century" Scientific American The Computer In The 21st Century, 1995, p. 78.

"Connectivity-The Future of Interactive Electronic Entertainment" The Red Herring, December 1994, pp. 46-48.

"The coolest capitalists" Forbes, September 25,1995, p. 162.

"Copyright Office OKs Disc Fees; ASCAP Offers Online Fee Calculator" Billboard, February 28,1998, p. 49.

"Copyright Scope Limited for Some Firms" The Wall Street Journal, March 10,1998, p. B5.

"Copyrights and copywrongs" The Economist, July 26,1996, p. 14.

"Cordless communications Spread thin" The Economist, October 9,1993, p. 92.

"Cyberspace Crafting software that will let you build a business out there" Business Week, February 27,1995, p. 34.

"Data communications Deluged" The Economist, July 22,1995, p. 83.

"The death of discs" .net, March 1995, p. 41.

150 Economist years: Business, Finance and Science "The death of telephony" September 1993, p. 75.

"Digital Hollywood" The Red Herring, January 1998, p. 61.

"Digital Underground" Rolling Stone, September 9,1994, p.40.

"Digital Underground Bootlegging makes inroads on the info superhighway" Rolling Stone, September, 8,1994, p. 40.

"Digital Watermarks Often Fail on Web Images" CyberTimes The New York Times on the web, November 11,1997, p. 1.

"disc junkie" Wired, July 1995, p. 135.

"Don't tell it to the Spartans (nor, indeed, to anyone else)" The Economist, February 18, 1995, p. 93.

"Double or quits", The Economist, May 30,1992, p. 79.

"The Economy of Ideas: A framework for rethinking patents and copyrights in the Digital Age" Wired, March 1994, p. 85.

The Economist A Survey of the Computer Industry, "The third age" September 17,1994.

The Economist A Survey of the Internet, "The accidental superhighway" July 1,1995.

The Economist A Survey of Television, "Feeling for the future" February 12,1994.

Electronics Industries Association reports, June 1994

"The end of the line" The Economist, July 15,1995, p. 69.

"Everyone else is doing it - so why don't we?" Music Week, May 20,1995, p. 9.

The Fire of Invention, Michael Novak, 1997.

"Flying Toasters" Wired, May 1994, p. 64.

"For 3DO, a Make-or-Break Season" The New York Times, December 11,1994, section 3, p. 1.

"Fran-On-Demand" Wired, September 1994, p. 60, 62.

"Friend of Bill" The Economist, November 1,1997, p. 69.

Game Over, David Sheff, 1993, p. 288, 419.

"GE 73 3/8 GI 18 5/8 GM 57 1/2: The Ticker Explained" The New York Times, Sunday, January 18,1998, p. 5.

"The Gee-Whiz Company Silicon Graphics Turns 3-D Images Into Stunning Profits" Business Week, July 18,1994, p. 62.

"Geekdom gone gaga" Forbes, March 9,1998, p. 44.

"GlobalNet, Sony Ready Pay-Per-Play Music" Billboard, July, 26,1997, p. 66.

"Gore's Law" The Economist, January 15,1994, p. 72.

"Growth in home businesses getting Americans wired like never before" The Japan Times, August 8,1995, p. 11.

"Hand-Held Combat How the Competition Got Ahead of Intel In Making Cheap Chips" The Wall Street Journal, February 12,1998, pp. A1, A11.

"The Hard And Soft Sell Technique" Billboard, January 7,1995, p. 92.

"High noon for Billy the Kid?" The Economist, June 24,1995, p. 59.

"'Honey, They're Downloading Our Song'" The Wall Street Journal, July 17,1997, p. B1.

"How the people of Rochester saw the future and yawned" The Economist, February 25,1995, p. 67.

"Hunt the geek" The Economist, November 22,1997, p. 81.

"Infobahn Warrior" Wired, July 1994, p. 86.

The Information Highway section The Red Herring, February 1995, p. 18.

"Innovation, Not Invention" Wired, April 1995, p. 128.

"Instant interaction" .net, March 1995, p. 22.

"Int'l Committee Bows Out Of Debate On DVD Sound" Billboard, November 29,1997, p. 6.

"The interactive bazaar opens" The Economist, August 20,1994, p.49.

"Internet Brands bite back" The Economist, March 21, 1998, pp. 78, 81, 82.

"Internet Bulls Get on Line for Performance Systems IPO" The Wall Street Journal, March 28,1995, p. C1.

"The Internet is Mr. Case's Neighborhood" Fortune, March 30,1998, pp. 69-80.

"An Inquiry into the Merits of Copyright: The Challenges of Consistency, Consent, and Encouragement Theory" Stanford Law Review, vol. 41, 1989, pp. 1365-1477.

"ISDN Back to the future" The Economist, January 7,1995, p. 54.

"Is Going On-Line Worth The Money?" Fortune, June 13,1994, p. 104.

"Is it tellynet or netelly?" The Economist, December 13,1997, p. 10.

"Is the Internet overhyped?" Forbes, September 23,1996, pp. 108-117.

"I-TV: Hit Or Myth" Informationweek, August 29,1994, p. 12.

Japanese Article on Digital Media, Nihon Keizai Shimbun, August 25,1994, front-page.

Japanese Article on New Digital Game Products, Nihon Keizai Shinbum, August 30,1994, p. 13.

JASRAC schedule of royalties for rental of compact discs in Japan.

"Jump Starting Desktop Multimedia Applications" Investor's Business Daily, September 14,1994, p. A6.

"A 'Killer App,' Indeed What's Hot? Software That Rubs Out Software" The New York Times, March 27,1995, p. C1.

"Koppelman, Prudential Offer C'right Loans" Billboard, February 14,1998, pp. 6, 89.

"Leave Digital Distribution to Sci-Fi- Here's Your Future" Billboard, December 27,1997, p. 66.

"Let the digital age bloom" The Economist, February 25,1995, p. 13.

"Lights! Camera! Dial Tone!" Time, September 5,1994, p. 56.

"Little Microware Aims to Be a Multimedia Giant" The Wall Street Journal, January 18,1994, p. B1.

"Majors Cut Costs Via Industry-Only Sites" Billboard, August 23,1997, p. 58.

"A Market Waiting to Happen" The Recorder, July 22,1997, pp. 1, 12.

"MCI to Offer Internet Access, Electronic Shopping" The Wall Street Journal, March 27,1995, p. A3.

"Media Mania" Business Week, July 12,1993, p. 96, 97, 100.

"Microsoft's Co-Founder Invests $1.75 Million in Metricom Stake" The Asian Wall Street Journal, October 7,1993.

"Mix Your Own Disk" The Wall Street Journal, March 20,1998, p. W6.

"More than just a label" .net, March 1995, p. 53.

"Movers and shakers" The Economist, January 24,1998, p. 63.

"Multimedia Breathless" The Economist, July 11,1994, p. 64.

"Multimedia hype exceeds its performance" San Jose Mercury News, February 12,1995, p. F1.

"Multimedia Meets the Web- Are Publishers Doomed?" The Red Herring, July 1995, p. 119.

"Multimedia's no-man's land" The Economist, July 22,1995, p. 59.

"Multimedia The Oracle speaks" The Economist, February 19,1994, p. 65.

"Multimedia's yellow brick road" The Economist, December 4,1993, p. 69.

"Multimediators" The Economist, April 16,1994, p. 18.

"The music business Getting ahead" The Economist, July 1,1995, p. 58.

"Music To His Ears" Informationweek, May 2,1994, p. 33.

"Muzak versus the mouse" The Economist, August 30,1997, p. 48.

"Muzic.com Assembles Cyber-Tools" Billboard, February 21,1998, p. 53.

"The Nature and Function of the Patent System" Journal of Law and Economics, vol. 20, October 1977, pp. 265-290.

"Net Nightmare For The Music Biz" Business Week, March 2,1998, pp. 89-90.

"The new electronic messiah" The Economist, August 5,1995, p. 60.

"Nintendo Battles for Its Life" Upside, October 1995, p. 50.

"On-line newspapers Hold the front screen" The Economist, February 11,1995, p. 60.

"On-Line Services Try to Define Their Identities" The Wall Street Journal, July 12,1995, p. B1.

"Photos on your desktop" Forbes, March 27,1995, p. 118.

"Picture imperfect" The Economist, May 28,1994, p. 61.

"Play a Sad Tune for 1995 Record Sales" The Wall Street Journal, September 14,1995, p. B1.

"Plug and play" The Economist, June 24,1995, p. 77.

"Plugged In America Online Well-Situated To Capture Market Lead In '95" Investor's Business Daily, February 6,1995.

"Pop music Eros is coming" The Economist, February 21,1998, pp. 66-67.

"Prodigy Is In That Awkward Stage" Business Week, February 27,1995, p. 54 B-A.

"Products and Services for Computer Networks" Scientific_American_The_Computer_In_The_21st Century, 1995, p. 102.

"Ramming Speed" The Economist, August 13,1994, p. 74.

"Replicators Cite Growing Burden Of CD Patent Fees" Billboard, August 16,1997, p. 1.

"Representative ITV Services" BYTE, February 1993, p. 141.

RIAA reports

"The Rights Stuff" Electronic Musician, November 1997, pp. 126-129.

"Roll your own CDs" The Economist, March 14,1998, p. 14.

"SESAC In Deal For New Music Detection System" Billboard, January 24,1998, pp. 8, 101.

"The (Second Phase of the) Revolution Has Begun" Wired, October 1994, p. 116.

"The Sex Industry Giving the customer what he wants" The Economist, February 14,1998, pp. 21-23.

"Shape Shifter" Wired, April 1995, p. 88.

"Shareware Game Maker" Wired, April 1995, p. 155.

"Shopping in peace" Forbes, March 14,1994, p. 94.

"Sign here" The Economist, July 27,1996, p. 58.

"Smart marketing via the Internet" Forbes, September 23,1996, p. 218.

"So much for the cashless society" The Economist, November 26,1994, p. 23.

"Sony, Philips Showcase Super Audio CD Format" Billboard, October 11,1997, p. 12.

"Sony CEO Stresses Retail Role In Digital Future" Billboard, January 7,1995, p. 77.

"Sony Music Has Upbeat Tune as Label Turns Around" The_Wall_Street_Journal, February 23,1998, p. B4.

"The South rises again" The Economist, March 7,1998, p. 89.

"Standard bearers" Forbes, March 27,1995, p. 112.

"Swap you" The Economist, February 7,1998, p. 83.

"Taking the scenic route" The Economist, April 16,1994, p. 67.

"Tale of two Internetters" Forbes, September 11,1995, p. 48.

"The tangled webs they weave" The Economist, October 16,1993, p. 23.

"Technology beyond the CD" Industry Surveys, March 12,1992, p. 31.

"Telecoms deregulation Competition calling" The Economist, July 1,1995, p. 59.

"Telecosm The Bandwidth Tidal Wave" Forbes ASAP, December 5,1994, p. 163.

"Terminal Music Biz" Mondo 2000, 12, p. 43.

"Thank you for the music" .net, March 1995, p. 49.

"Theatrical dram up close Intimate magnificence" The Economist, September 20,1997, p. 97.

"This isn't Napoleon at Austerlitz, but..." Forbes, December 19,1994, p. 104.

"Thrills and Chills of Marketing a CD-ROM Adventure" The New York Times, November 27,1994, section 3, p. 3.

"Time Warner's Orlando Test to Start-Finally" The Wall Street Journal, December 7,1994, p. B1.

"Toys Now, Computers Tomorrow?" The New York Times, April 20,1994, p. D1.

"The Uncertain Outlook For 3DO/Experts Give Company Mixed Reviews," The San Francisco Chronicle, July 25,1994, p. D1.

"TTR Inc., Nimbus To Fight Piracy With DiscGuard" Billboard, December 13,1997, p. 39.

"Unauthorized Recordings" The Economist, from International Federation of the Phonographic Industry data, November 26,1994, p. 122.

"Universal Service (An Idea Whose Time Is Past)" Wired, September 1994, pp. 153-154.

"Utilities and telecoms The third wire" The Economist, January 28,1995, p. 62.

"Viacom Doesn't Suck!" Wired, April 1995, p. 110.

"The Virtual Studio Computers come to Tinseltown" The Economist, December 24, 1994-January 6,1995, p. 87.

The Wall Street Journal, August 4,1994, p. B6.

"Watch Out For The CD-ROM Hype" Fortune, September 19,1994, p. 127.

The Web Magazine, Listen Up! Music Rocks The Web, July 1997, issue covering the music industry.

"Web 'piracy' gives Pearl Jam fans taste of new album" The Miami Herald, December 18,1997, p. 5F.

"Where's the money?" Forbes, January 30,1995, p. 100.

"Why they call it Harvard College" Forbes, March 9,1998, pp. 50-51.

"Beleaguered Microsoft Why Bill Gates should worry" The Economist, December 20,1997, pp. 100, 102.

"Will On-Line Shopping Come Of Age In The Second Half Of The '90s?" Investor's Business Daily, January 11,1995, p. A4.

"Will Video Game Machines Turn Into PC Killers?" The New York Times, January 8,1995, p. F7.

"Wire Pirates" Scientific American The Computer In The 21st Century, 1995, p. 186.

"Wired for sound" .net, March 1995, p. 39.

"Wireless networks Auction fever" The Economist, December 3,1994, p. 77.

"Wireless Mobile Communications" BYTE February 1993, p. 148.