7,271 Words

Sigsaly

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The astonishing work by William and Elizabeth Friedman in breaking the Japanese "Purple Code" during World War II has often been described, as has the equally important and amazing feat by Alan Turing and his group in England in unscrambling the way in which the "Enigma" machines used by the Nazis had worked. The former accomplishment enabled the US to shoot down Admiral Yamamoto's plane in the Pacific and by doing so, helped to win the Battle of the Coral Sea. The latter feat helped to save Great Britain during the Air War and to wipe out the deadly U-boat menace in the North Atlantic.

There were other cryptographic accomplishments carried out at the Bell Laboratories that were less well-known. One of them was the use of "Voice Print" analysis to defeat the effects of an electronic speech scrambler employed by the Japanese fighter pilots to communicate with each other by radio during combat. Electrical engineers at Bell looked at the frequency spectra from recordings of the scrambled messages in Japanese and re-arranged the various frequency bands until they obtained a pattern characteristic of human speech. At that point, someone who knew the language could understand the messages. An electronic de-scrambling apparatus based on the same frequency-band rearrangement method was then packaged for our own use in the Pacific. Although an impressive accomplishment, it wouldn't have been too helpful to our fighter pilots unless they had also taken a crash course in Japanese. (The situation reminded me of the story about one of our fighter groups composed of American Indians. Their speech in Navaho must have been very confusing to the Japanese pilots, even if they knew English.)

But one of the most impressive technological feats during the War went completely unreported until it was declassified in 1976, over *three decades* later! This was the secret telephone transmission system developed at the Bell Laboratories in the early 1940's called the "X-System," or "Sigsaly", and nicknamed "The Green Hornet" by the people who worked on it. The Signal Corps gave it the name "Sigsaly", but the system was so wrapped in secrecy that the origin of that code word remains obscure. Suggestions have ranged from a possible Nordic God of War to some acronym based on "Signals and Allies." When the method was finally revealed to the public, my father was the only one left alive in the world who knew how the system had actually worked. Much to my mother's alarm, people ranging from military officers to editors of IEEE journals descended on their home to quiz him for an "oral history" of the project. (I have no idea what happened to the tape recordings made during those interviews; they're probably locked up in some inaccessible vault in the National Security Agency.) Dad was in the late stages of heart failure at that time and was "popping" nitroglycerin tablets as if they were candy. My mother feared those long discussions hastened his death, but I think that Dad's long-developed sense of stewardship forced him to complete that one final project. Indeed, the last paper Dad wrote was a comprehensive technical description of the system that was published a few months before he died.[1] The technical language in the article probably drove off the average reader, inspite of a "number of human-interest type anecdotes" described. Mom, inspite of her feelings, did type and edit the paper for him.

I suppose I should have guessed that he was working on something like that secret telecommunications project at the time. I remember that he had become very concerned with cryptographic methods during that period (circa 1942) and recall him showing me how the random key telegraph code used during the first World War had actually worked. (I had received a pair of battery-operated telegraph keys for Christmas that year and spent some time learning the Morse Code.) That secret transmission method was sometimes called the "Vernam System", after the man who published an article describing it in 1926.[2] It is easiest to explain the concept behind the method using messages and random keys that each consisted of a long string of binary digits.

In a sense, Morse Code, itself was one of the earliest forms of digital communication. The dots and dashes used in Morse Code can be thought of as a string of "zeros" (dots) and "ones" (dashes) making up a sequence of binary digits. For example, using this convention to put the message

	H	E	L	L	O
into Morse Code yields	0000	0	0100	0100	111

which could be strung together into one 16-digit binary sequence which we will call the "Message." But we'll retain the spaces between the letters (which were pauses in the original pulse train coming over the telegraph wire) in order to put the message back into

[1] William R. Bennett, "Secret Telephony as a Historical Example of Spread-Spectrum Communication", - initially in the *IEEE Transactions on Communications*, Volume **COM-31** (January, 1983), pp. 98 - 104; reprinted later in the book, *Spread-Spectrum Communications*, edited by Charles E. Cook *et al* , IEEE Press (New York, 1983), pp. 50-56. The material in the present essay is based on those articles, numerous conversations with my father, and the collection of papers I found in Dad's files after he died. Much of the testimony by key witnesses was rounded up by Dr. Robert Price, a much younger Fellow of the IEEE who had developed a strong interest in the history of "spread-spectrum" technology --- ranging from an early war-time patent by the movie actress Hedy Lamarr to the creation of Sigsaly, itself.

[2] G. S. Vernam, "Cipher Printing Telegraph Systems for Secret Wire and Radio Communications, *AIEE Journal*, Volume **45**, pp. 109-115 (Feb., 1926); also see, *AIEE Transactions*, Volume **45**, pp. 295-301, Feb., 1926.)

Morse Code at the receiving end. If we were to add the "message" to a random key the result might be:

	"Message"	0000	0	0100	0100	111
+	"Random Key"	0111	1	0000	1111	011
=	"Coded Message"	0111	1	0100	1011	100

The "Random Key" is another string of binary digits which might have been obtained by flipping a coin, calling "Tails" = 0 and "Heads" = 1. At this point, attempting to unscramble the coded message using the conventions of Morse Code would yield

J T L Y D

-- a far cry from "H E L L O".

The sum of the "Random Key" and the "Message" is obtained using a simplified rule for binary addition on each pair of digits in which no attempt is made to carry over digits from one column to the next:

$$0 + 0 = 0$$
$$0 + 1 = 1$$
$$1 + 0 = 1$$
and $$1 + 1 = 0.$$

To get the original "Message" back again, we only need subtract the same random key from the coded message using the (inverse) rule for binary subtraction:

$$0 - 0 = 0$$
$$0 - 1 = 1$$
$$1 - 0 = 1$$
and $$1 - 1 = 0.$$

Thus,

	"Coded Message"	0111	1	0100	1011	100
—	"Random Key"	0111	1	0000	1111	011
=	"Message"	0000	0	0100	0100	111

which gives back in Morse Code H E L L O

The binary arithmetic can be done very simply and rapidly without computers by using pairs of "coincidence" and "anti-coincidence" circuits (or, in technical jargon, "AND" and "OR" gates.)

It seems intuitively likely that adding a random string of binary numbers to the original message would give a result that is also random. Proving that rigorously is not so easy. (As one of the mathematicians at Bell Labs said of the later random key coding scheme used in the Sigsaly system after working on it for a while, "I can't prove that the coded signal is random. However, I can't prove that it is not, either.") It is, of course, important never to use the same string of random digits twice; otherwise an enemy as clever as Alan Turing might be able to unscramble the key from statistical properties of the source language. Although it is straightforward in the above example to recover the original message by subtracting the same binary key, the starting points on the two sequences have to be precisely the same. If the key were misplaced by only one digit from the original starting point, the result would be another meaningless string of random numbers.

What I didn't know when Dad initially explained the basis of the Vernam system to me back around 1942, was that he was working hard to put this type of thing into practice, based on digital transmission of signals derived from the audio spectrum of speech. Dad told me later on that he was required to apply for "Crypto-Clearance" to work on the project. That involved having the FBI interview all of Dad's relatives, including second cousins living in Europe of which there were quite a few. The clearance process took so long that the war was over before he obtained it. He, of course, worked on the project throughout the war anyway.

At one point the Bell Labs people had invited Alan Turing to come over from England to see the system work and discuss possible weaknesses in the design that an enemy might somehow use to break the code. Turing was scheduled to visit the Labs in New York City in December of 1942. When he arrived, the security people at the Labs wouldn't let Turing in the front door. At the time Dad thought it was because they might regard him as a security risk! (The fact that he was a homosexual seemed to worry the British security people; they actually forced him to take female hormones, with the result that he grew breasts -- something that probably contributed to his eventual suicide.) The truth about Turing's Bell Labs "visit" wasn't learned until long after the War when documents in General George C. Marshall's Library were declassified. The correspondence on the matter was revealing:

December 2, 1942. J.G.Dill (British Joint Staff., Offices of the Combined Chiefs of Staff) to General Marshal:

> "... I understand now that the construction of your scrambling device ... is considered too secret to allow Dr. Turing to look in on it."
>
> "... Dr. Turing is absolutely reliable and is in on every secret we possess about cryptanalyst ... devices. I am told we are working together on these questions in full cooperation."
>
> "Can you lift the ban on Dr. Turing?"
>
> "Yours ever,
>
> J. G. Dill"

December 5, 1942. Maj. Gen. V. Strong, "Memo for the Chief of Staff":

Subject: Dr. A. M. Turing.

"Dr. Turing came to this country as a representative of the British Post Office, supposedly as a Cryptographer and Cryptanalyst. He did not contact this office ... However, Captain Hastings, who is ... a liaison officer between the British Admiralty and the Navy Department and who has no standing whatever with the War Department, did approach an officer in the Signal Corps .... and asked that permission be granted as requested. A few days later Colonel Crawford, S.C., received a call about 10:30 in the morning stating that Dr. Turing was leaving for New York on the afternoon train and requesting that arrangements be made for him, Dr. Turing, to visit the Bell Laboratories."

"This incident represents just one more pain in the neck resulting from the consistent practice of British representatives...using back door methods to gain information....not only in regard to this...device...but also on secret code missions and devices, permission to see which has always been denied representatives of foreign governments, including the British...."

"Instances of this kind will constantly occur until the British are educated ...[to]... deal on the proper level after having been properly introduced and accredited ...."

... V. Strong,
Major General,
A. C. of S., G=2"

December 9, 1942: Gen. G. C. Marshall - Memorandum for Field Marshal Sir John Dill:

Dear Dill,

"In answer to your note regarding Dr. Turing, I find that this project has been placed in the ultra secret class and information concerning it has been restricted to the fewest possible officers. I am told this same policy is being followed by your intelligence people and that there is not interchange of information regarding these ultra secret developments."

"I regret that Dr. Turing should have been embarrassed by a last-minute refusal after he had made plans to go to New York. The misunderstanding in this matter was due to Dr. Turing's having conferred with subordinates in the War Department who do not have the authority to decide these questions. Such difficulties will be eliminated if requests are made to our Military Intelligence Division, and I have instructed that division to extend him every possible courtesy."

"Faithfully yours,

G. C. Marshall
Chief of Staff"

One might say that with Allies like that, who needs enemies? As much as anything, it seemed like the request was turned down because it didn't go through "proper channels." Dad and a couple of other people working on the project did discuss the system with Turing in a secluded place outside the Labs. Turing seemed convinced the system would be totally unbreakable, which, of course, was their chief matter of concern.

About that time, the American security people had an eight-foot-high, chain-link fence with barbed wire on top erected around the Bell Laboratories compound at Murray Hill. Dad noticed that the barbed wire was facing *inward*, rather than outward, as if to keep all the scientists imprisoned. (The new buildings themselves did indeed look like a penitentiary.)

When I learned about Sigsaly myself several decades later, the system they had developed was totally amazing to me in many regards -- the mere fact that it had worked at all being at the top of the list. Indeed, one of the people who designed electronic circuits for the project during the war named Orlando J. Murphy had enunciated an important principle that has since come to be widely known as "Murphy's Law" in description of the difficulties they encountered. As originally formulated, Murphy's Law stated, "You can always depend on complicated systems to break down in the worst possibly way under the worst possible conditions!" The X-System was kept so secret for so many years after the war ended that Murphy's most famous contribution to the project was totally obscured. Murphy was a man of eclectic interests. For example, he once used some frequency measuring equipment he had built to investigate the concert pitch (supposedly, based on the international convention that "A" above middle "C" should be tuned to 440 Hz[3]) of major orchestras and soloists who broadcast live concerts over the air.[4] He found that out of 750 observations, the mean value of "A" was 441.3 Hz, with extreme variations from 434 Hz for a dance band up to 448 Hz on two occasions for string quartets. Orchestras varied at random during the course of a given selection by as much as 2 Hz. Not surprisingly, string instruments showed the most variation in pitch and were generally sharp. However, singers showed so much moment-to-moment variation as to make the measurements of questionable value. Dad told me once that he had written up a brief history of Murphy's Law after the war and tried to get it published in one of the electrical engineering journals. The note was rejected, probably because it was merely a "human interest story." Inspite of all the secrecy, the basic concept of "Murphy's Law" leaked out and has since popped up all over the world -- but without Orlando's name on it.

[3] The term Hertz, abbreviated Hz, was introduced long after World War II by the IEEE (the Institute of Electrical and Electronics Engineers) to replace the previous self-evident unit of "cycles per second" – possibly to keep interlopers out of the field.

[4] Orlando J. Murphy, "Measurements of Orchestral Pitch", *Bell Laboratories Record,* Vol. **19**, No. 5, pp. 143 - 146 (January 1941). The Bell Laboratories Editor was quick to point out that this study "was undertaken by way of Mr. Murphy's personal interests and was carried out in his own home" [and on his own time.]

The X-System had incorporated nearly every major electronic development made at the Labs during the previous decade. The 1930's had been the "heyday" of audio engineering at the Bell Laboratories. Harvey Fletcher was then Head of the Physical Research Group and collaborated with his friend Leopold Stokowski and the entire Philadelphia Symphony Orchestra in many of those early experiments. Nearly every major later development in sound recording, transmission, and reproduction was anticipated at that time. Those inventions ranged from the development of the negative feedback amplifier[5] and record cutter, through stereo long-playing records (circa 1932), the use of "companders"[6] of the type later commercialized by Dolby and others to enhance the dynamic range of recording media, through the digital recording of speech and music and fundamental studies in psychoacoustics -- something Harvey Fletcher actively pursued himself.[7] High-fidelity loudspeakers and horns and multi-channel stereo systems were developed for use in motion picture theaters. Some results of this collaboration were used by Walt Disney in the creation of the movie *Fantasia*. Other developments in technology, such as audio spectral analysis, the "Voice Print" and speech synthesis were more specifically aimed at telephone transmission. Much of this work came to an end when the Supreme Court decided shortly after World War II to force the Bell System out of the commercial audio business. AT&T had unwisely forced its customers to rent the audio equipment, rather than allowing them to purchase it. That alone made a number of powerful people in other companies very angry. After the decision by the Court, AT&T not only stopped nearly all research in the audio field, but also dumped most of their high-quality audio components on the market at far below actual value. (I recall buying as many Western Electric 728B and 755A loudspeakers at that time as I could afford on my meager budget as a college student.) Much later when I collaborated in the discovery of

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[5] The negative feedback technique increases the stability of an amplifier and reduces inherent distortion by taking some of the output and feeding it back out-of-phase to the input. The idea was conceived by Harold S. Black in August 1927 while he was commuting to the Bell Labs on a Lackawanna Ferry and the initial disclosure was written on a page of the *N. Y. Times*. (See the retrospective article written by Black entitled "Inventing the Negative Feedback Amplifier" in the *IEEE Spectrum* pp. 55-60 (December, 1977). His first open publication on the method was given much later in *Electrical Engineering* Vol. **53**, pp. 114-120 (January 1934).

[6] Because the dynamic range of early recording media -- especially, movie sound tracts -- was extremely limited, the Bell Labs engineers developed a system in which the original source was fed through a circuit that reduced the amplitude of the recorded signal by an amount that increased with higher values. In the playback mode, an inverse correction was made to restore the signal to the original relative values. The process was called "companding" for "compression-expansion" and effectively reduced the noise level in the recorded sound.

[7] See, Harvey Fletcher and W. A. Munson, "Loudness, Its Definition, Measurement and Calculation," Bell System Technical Journal Vol. **12**, pp. 377-430 (1933). The "Fletcher-Munson curves" (Fig. 4 in the paper) are well-known to audio aficionados and describe the variation of apparent "loudness" that results from the nonlinear response of the human ear at different frequencies. At very low sound intensities, the sensitivity of the ear falls off rapidly both in the bass region and in the treble. But at intensity levels approaching the threshold of pain, the relative response is more nearly constant.

the first gas laser at the Bell Labs[8], I recognized some of the memorable pieces of apparatus from that period gathering dust in the basement of one of the buildings at Murray Hill.

In addition to being the first completely secret telephone communication system ever made, Sigsaly also represented the first realization of *digital* recording and transmission of audio signals. (Some people seem to think that that was a Japanese invention after the war!) It also incorporated a number of technological developments that had been of such importance as to warrant exhibition all by themselves at both the 1939-1940 New York and 1940 San Francisco World's Fairs. (I actually got to see the demonstrations at both places myself!)

Prior to the work on Sigsaly, only analog methods of sound recording and transmission had been used. In a way, the transition from analog to digital audio methods unnecessary was somewhat analogous to the transition from classical mechanics to quantum mechanics in the world of physics. Earlier sound recordings had all been based on electro-mechanical systems which took on a continuous range of values: for example, the voltages produced by a microphone varied continuously, as did the extent of vibration of the needle in the grove of a phonograph record. The excursion of the needle was proportional to the amplitude of the original sound wave (at least approximately.) Amplitude modulation on a radio wave similarly took on continuous values that were proportional ("analogous") to a microphone voltage, which in turn was derived from the continuous pressure variation of a sound wave on the microphone diaphragm. There were disadvantages in such a system. The noise level in such systems tends to grow from one stage to the next. If you made a recording of a recording of a recording ... the noise and distortion would build up to intolerable levels. The result is similar to making a Xerox copy of a Xerox copy of a Xerox copy. The first Xerox machines were also analog devices and after you had made a dozen copies of copies, the blurryness would make the document illegible. Similarly, writing with ink on a blotter is another (although extreme) example of a recording medium that adds noise noise and distortion to the signal; the ink spreads out in the medium and obscures the message.

It was realized by various people at the Bell Labs in the 1930's including my father, that those limitations could be overcome by breaking up the signals into specific quantized levels. One first has to decide what degree of granularity can be tolerated in the signal, for that determines the number of discrete levels into which the signal must be quantized. For example, if the signal is quantized using N binary digits (where $N = 1, 2, 3, 4,...$) it can be spread over a range of 2^N different values (where $2^N = 2, 4, 8, 16, 32,.....$) As noted by the old Greeks, that series builds up very rapidly with increasing N. (Witness the famous example of the grains of wheat on the chess board; if you tried to

[8] A. Javan, W. R. Bennett, Jr., and D. R. Herriott, "Population Inversion and Continuous Optical Maser Oscillation in a Gas Discharge Containing a He-Ne Mixture", Physical Review Letters Vol. 6, pp. 106-111 (February, 1961)

double the number on each successive square, you would have used up all the wheat in the world long before filling the board.) For N=1, the signal is divided into only two levels and the quality of a recording would be intolerable. But for N=16 (the sample size used in typical contemporary CD recordings), the number of different gradations, or quantization levels, is over 65,000. The maximum dynamic range of the most sensitive human ears corresponds to sample sizes of about 20 bits each. But far less resolution is required to understand human speech.

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The next thing one needs to consider is the number of samples per second needed to record or transmit the signal. That was shown in the 1920's by Harry Nyquist (also at the Bell Labs) to be twice the maximum frequency contained in the audio source.[9] Hence, if you want to make high-fidelity digital recordings of a symphony orchestra over the maximum range of hearing (about 20 kHz), you need to sample the signal over 40,000 times per second. (The Sony Company used a sample frequency of 44 kHz on the first CD recordings.) But you can only use the first half of that frequency range. Because spurious ("aliasing") signals are contained in the range above half the sampling frequency in the encoded signal, a sharp cut-off filter is used for playback above the maximum frequency needed.[10] Having digitized the signal into binary bits, it becomes easy to make identical copies of the original recording without *any* further build-up of noise or distortion. Copying each binary digit (or bit) is an all or nothing affair. For example, it is far easier to copy 16 separate pulses that vary from zero to one volt -- thereby generating a composite signal good to one part in 65,000 -- than it is to copy an analog signal that varies from zero to 1 volt in 65,000 gradations. There are other fringe benefits: Because the sampling can be done with a highly stable reference frequency, the recorded and transmitted signals are completely free of the "wow" and "flutter" that plagued early disc and tape recordings from speed variation in the recording medium. Similarly, the deleterious effects of Doppler shifts from motion in the ionosphere during radio transmission and satellite motion in current communication systems are eliminated.

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[9] The first derivation was given by Harry Nyquist in a paper entitled "Certain Factors Affecting Telegraph Speed", in *The Bell System Technical Journal* Vol. 3, pp. 324-346 (1924). This relation between maximum useable frequency and the sampling frequency is probably the most well-known of some five different "Nyquist criteria" in the communication field. One can easily see that the criterion makes intuitive sense: One obviously needs to have at least two samples over the period of the maximum frequency component to define an oscillating sinusoidal wave at the maximum audio frequency encoded. However, the derivation by Nyquist was given without the use of Fourier analysis (which would have been the easiest approach) and involved an individual style of mathematics that was hard for most engineers to follow and, in some cases, even to believe.

[10] The spurious signals above half the sample frequency occur due to nonlinear mixing of signal components with the sample frequency. One can see how that comes about by noting that the sampling occurs by multiplying a "gate voltage" (e.g., going briefly from 0 to 1 and back to 0 again) at the sample frequency with sinsusoidal components of the audio signal. The fundamental term in the spectrum of the gate voltage is a sinewave at the sample frequency. From elementary trigonometry relations, the product of two sinewaves at two different frequencies can be rewritten as the sum of two different sinewaves, one at the difference between the two original frequencies and one at the sum of those two frequencies. As the audio signal frequency sweeps upward above half the sample frequency, the difference-frequency signal sweeps downward throughout the entire audio band creating intolerable distortion products.

(These shifts would occur with an analog signal because of the relative motion between the source and the receiver.) Because the Dudley vocoder system used in Sigsaly only transmitted the time-variation of speech formants (at most 25 cycles/sec), a very low sample frequency (50 Hz) was needed. In addition, the trans-Atlantic radio transmission bands were plagued with noise, hence digitization of the signals played a doubly-important role. One of the most important advantages of digitization in that system was that it provided an easy way to add a random key to the transmitted signals.

The Vocoder (an acronym standing for "VOice CODER") was conceived by Homer Dudley in 1931 and developed by Dudley and his coworkers. It, together with the Voder (for "Voice Operated DEmonstratoR"), were the earliest electronic speech synthesizers ever made.[11] Using other developments by Dudley and his colleagues (especially the "Sound Spectrograph" and "Voice Print" analyzer)[12], Dudley had observed that the spectrum of the human voice could be broken up into the time variation of a small number of frequency bands (about 300 Hz wide) which he called "formants". The vocal chords provide an audio sound variable in pitch, but also rich in harmonic content that is fed through a transmission filter consisting of resonances in the mouth and nasal cavities. Those resonances are controlled by the tongue and muscles of the mouth so as to select different formant bands. The positions of the formants vary with the different vowel sounds and in the case of diphthongs, change in position relative to each other during pronunciation. In addition, there is a higher-frequency band of noise between about 4,000 and 10,000 Hz produced by the turbulent passage of air through the mouth and over the front teeth. That source creates "sibilants", or "sss" sounds. The human ear recognizes speech through the time variation of those formants, which typically vary quite slowly (generally at less than 25 Hz) compared to the complete spectrum of the normal human voice (perhaps up to 10,000 Hz.) Hence, a much smaller bandwidth can be used to transmit the basic information contained in a spoken message than would be required to send the entire sound of the voice.

Dudley set about to simulate the entire process electronically. With the Vocoder, the output from a microphone was passed through a series of filters that extracted the time-varying formants. To regenerate the voice, he reversed the process and used a relaxation oscillator rich in harmonics to simulate the sound of the vocal chords and fed its output through several filters representing the first few formants of the human voice. The

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[11] For a review of these developments, see Homer Dudely, "Fundamentals of Speech Synthesis" in the *Journal of the Audio Engineering Society*, Vol. 3, pp. 170-185, (October, 1955). The vocoder was first demonstrated (privately to a group of engineers, including my father) by Dudley at the Bell Labs in 1935 and publicly at the Harvard Tercentenary in September, 1936.

[12] An elegant review of this technology with lots of nice illustrations is contained in the book by Ralph K. Potter, George A. Kopp, and Harriet C. Green entitled *Visible Speech* (D. Van Nostrand Company, New York, 1947). Dad mentioned that Potter had another interesting idea at that time: the cordless telephone receiver. In his version, powdered iron filings would be sprayed with glue onto the customer's ear drums. The messages would then be transmitted magnetically to the ear drums from a coil mounted in the wall or on a table. Fortunately, the idea did not catch on. (Imagine walking under a power line!)

voltages derived from the original formant frequencies were used to modulate the output level from the corresponding filters. In addition, broad-band thermal noise was used to simulate the turbulent noises in the range from 4,000 to 10,000 Hz produced by air flow in the mouth and another voltage which was determined from the pitch of the original human voice was used to control the fundamental frequency of the relaxation oscillator. With the Vodor (which was the device demonstrated at the 1939 World's Fair), an operator at a keyboard controlled the amplitude levels from each formant along with the random noise amplitude and pitch of the voice. After considerable practice, the operator could produce understandable speech just by hitting different keys on the machine; the apparatus was really a "talking typewriter."

Homer Dudley was a close friend of my father's and a frequent visitor to our home. The last time I saw him was at my parents' 50th Wedding Anniversary. He died shortly thereafter. At the Anniversary party he promised to send me a tape recording of the early demonstration of the vocoder he had prepared for presentation at the Harvard Tercentenary in 1936. Unfortunately, he didn't know my mailing address and sent it to my father instead. It got filed away with an accompanying note in my father's rather awesome collection of papers and reprints. (Alas, it took four dumpster loads to dispose of those papers after my father died! My wife and I had no room for the collection and my mother needed to sell the house.) Consequently, I didn't come across Dudley's recording until after Dad had died, too. The recording was a delightful and very humorous explanation of the vocoder, which I played several times for the enjoyment of students in my courses at Yale University.

Another important component in the Sigsaly system was the Crystal Controlled Clock that had been developed by Warren Marrison.[13] As Dad described him to me, Warren was a near-genius type who had originally come to the Labs from Canada, but was difficult to control. When asked to grow crystals for a specified project, he tended to go off on some individualized tangent, such as growing them in the shape of a doughnut. He lived around the corner from us in Milburn, NJ and I used to play clarinet sonatas with his wife Grace, who was a very good pianist. Warren had an amateur interest in conducting music and had organized a youth orchestra that rehearsed in one of the local schools. He probably had learned from Harvey Fletcher that Stokowski liked to conduct with a dB (or decibel[14]) meter on the podium -- something that had been provided to him

[13] See the review by W. A. Marrison, "The Evolution of the Quartz Crystal Clock", in the *Bell System Technical Journal* Vol. **27**, pp. 510-588, (July 1928.)

[14] The "decibel", abbreviated simply as "dB" is a logarithmic measure of relative intensity. It is defined mathematically as 10Log_{10}(Intensity Ratio). The unit originally defined was the "bel" (named in honor of Alexander Graham Bell, inventor of the telephone, but misspelled). Unfortunately, that unit represented too large an intensity change for many applications. Hence, the decibel (or 1/10 of a bel) was generally adopted in practice. The original definition was made in 1923 in terms of the intensity loss in a one-mile length of "standard" telephone cable. [See, W. H. Martin, "Decibel - The Name for the Transmission Unit" in *The Bell System Technical Journal* , Vol. **8**, pp. 1-2 (1929)]. By coincidence, 1 dB turned out to be about the smallest change in sound intensity that the average listener could detect. Sensitivity of the ear is roughly

during the early experiments with enhanced dynamic range recordings of the 1930's. Warren could be a little unpleasant. One evening when we were rehearsing the variations on the Mozart aria "La ci darem La Mano" by Beethoven for a concert we were to give in the local junior high school, I asked him (largely out of politeness) if he had any suggestions. He had been sitting in an easy chair in their living room listening while his wife and I played. He commented acidly, "I'd prefer it if you could increase your volume in that first crescendo passage by about 6 dB, and you can go ask your father what that means." Grace turned to him and snapped, "Why don't you just shut up!" It seemed like a strange conversation to hold after the performance of a beautiful love song.

I learned later that the Marrisons were in the throes of divorce. Although my mother was very fond of Grace and remained in touch with her for many years afterward, she said that "Warren liked to play silly party games after dinner such as Spin the Bottle so that he could kiss all the wives." The Marrisons had two very smart daughters. The older one, Joyce, went into astronomy. (She once told me she had ruled out physics as a career because she didn't like Bessel Functions.) The younger one, Ruth, was my age and had *very* sharp finger nails. I used to sit behind her in third grade with her pigtails dangling irresistibly on my desk. Somehow, one of them wandered over into my ink well one day. I doubtless deserved the clawing I received as punishment. Ironically, Ruth went on to marry a very capable young electrical engineer named Bob Mathes who was the son of Robert C. Mathes, one of the co-inventors of the Sigsaly system. When I last heard of the elder Mathes, he and his wife had retired to an "Avocado Ranch" in California and were collecting dolls as a hobby. [The notion of an "Avocado Ranch" struck me with amusement; I imagined a bunch of gauchos riding around the ranch, spinning lariats over their heads in order to lasso escaping avocados.] In any case, the Marrison crystal-controlled clock worked extremely well and was based on a frequency-stabilized quartz crystal oscillator. The version used in the X-System employed a quartz crystal resonant at 100 kHz that was stable to within one part in ten million. (That's equivalent to an error of about three seconds in one year.)

My father's main contribution to the project was in the mathematical analysis of Pulse Code Modulation (often abbreviated as PCM) systems.[15] The data transmission method for the speech signals was to be based on digital encoding of the voice formants and important questions arose regarding the minimum sample rates needed, the sampling

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logarithmic - something known as Fechner's Law in psychology. Fletcher and Munson (1933, op. cit.) in their psychoacoustic studies concluded that a 10dB increase in sound intensity ratio was perceived approximately as a doubling in "loudness". It doesn't matter whether the initial level is that for the rustling of leaves or a fortissimo chord on the piano. To give an apparent doubling in the sound level, they conclucded that one had to increase the physical intensity by a factor of ten. But the conclusion was subjective. Others have since suggested that a doubling of the apparent loudness only requires an intensity change of about 6 dB -- or a factor of about four in the intensity ratio.

[15] See the review by W. R. Bennett in *Introduction to Signal Transmission*, (McGraw-Hill, New York, 1970), pp. 231-233. I'm afraid that when Dad published this book, he had not realized the X-System was still classified.

method and the sample sizes required. (Ultimately they adopted a "hexary" or six-level quantization scheme rather than a "binary" system. Dad humorously suggested that the entities should really be called "higits" rather than "digits", but the suggestion didn't fly. Later, the Bell Labs mathematician John Tukey was more successful in getting the word "bit" accepted as a shorthand for "binary digit.") After the war, Dad put together a number of the analyses he had done on those problems in the PhD thesis he submitted to the Columbia University Physics Department. He gave his thesis a title carefully chosen to emphasize its relationship to problems in physics.[16]

Although full of exceedingly complicated engineering details, Sigsaly or the X-system basically worked as follows:

Secrecy was to be maintained using a variant of the Vernam telegraph transmission system used during World War I in which a never-repeated random key was added to the signal at the transmission end and subtracted at the receiving end. The best way to add and subtract the random key was by digital means. The method required time-synchronization of the same random key to within ±0.001 second at both ends of the line, a requirement that was easily met by incorporating Marrison's crystal controlled oscillator and count-down circuitry. The random key sources consisted of identical disc records in which the recorded wave was the sum of 12 voice-band carriers, each of which was modulated by a train of hexary pulses whose amplitudes were obtained by six-level quantization from a gas tube noise source and stored on a nearly endless succession of 15-minute disc records. There was an armed guard in the room where the master records were made and one person in the group had the responsibility of taking each master record to a pressing plant in Manhattan where two (and only two) identical copies of each master key were made, after which the master itself was destroyed. Identical sets of the random key were thus made available at the transmitter and receiver locations. The records were destroyed immediately after use and a new identical pair was quickly substituted. Two turntables were used at each end for each communication direction so that one could go smoothly from one random key to the next merely by throwing a switch. (A second set of identical key records and turntables was needed at each end so that two-way communication could be established without compromising the system.) The records were played continuously day and night so that there would be no apparent change in the quality of the transmitted signal that was sent over the normal radio telephone bands at about 15 MHz. Pulses from Marrison's oscillator were used to synchronize the play-back turntables. The system for the most part did not require "anti-jamming" technology. However, at one point they were bothered by a German radio station operating on the same radio transmission band. They were able to make out the station's call letters and turned them over to the Air Force; shortly afterward the station went off the air. A self-destruct (thermite bomb) was built into the system that could

[16] W. R. Bennett, "Spectra of Quantized Signals", *The Bell System Technical Journal* Vol. **27**, pp. 446-472 (1948).

weld everything together in case of imminent capture, but that part of the design was never used.

Ordinary telephone microphones (made with carbon particles that were compressed by the sound waves so that the resistance of the microphone changed) did not have enough bass response below 200 Hz to work well with male voices, so a high-quality moving-coil microphone was designed to fit the hand set. The improved microphone was nicknamed the "Eight-Ball" because the telephone transmitter looked like the Eight Ball from a pool table. The output from that microphone was fed into Homer Dudley's vocoder system and the various formants were extracted. The amplitude contained in twelve vocoder channels, each of which had a bandwidth from 0 to 25 Hz, was digitized within six discrete levels. The basic pitch control was derived from 36 discrete levels, distributed logarithmically. The digital sampling was done at 50 Hz (twice the bandwidth of each vocoder channel.) The twelve enciphered pulse chains were then sent across the ocean by frequency-modulating 12 carrier frequencies that were uniformly and widely spaced over the entire radio telephone transmission band. (The wide spacing was used to reduce the effects of fading on the radio-telephone signal.) At the receiving end, the 12 different FM signals were separated by narrow band filters, and detected. The synchronized random noise key was then subtracted digitally from each vocoder channel and used to reconstruct the speech in the manner of the Dudley vocoder. Because very limited bandwidths were used, the speech had a mechanical quality that made personal recognition of the voices impossible. Nevertheless, the information transmitted by the formant envelopes made the messages quite understandable. (There was a slight problem transmitting female voices because they incorporated much higher frequencies. Sigsaly worked best on deeper, male voices.)

Terminals for these systems were used from mid-1943 until the end of the war and installed in Washington, London, North Africa, Paris, Hawaii, Australia and the Philippines. The first one was located in Washington, DC, the next was near Prime Minister Churchill's residence at No. 10 Downing Street (actually, in the sub-basement of an adjoining department store), a third was contained on a barge hauled behind Admiral Halsey's Flagship in the Pacific, a fourth was stored in a wine cellar in Algiers, and so on. According to General Crawford, Roosevelt had specifically requested that the Washington system be installed in the Pentagon rather than in the White House. He was aware of Churchill's nocturnal habits and felt that Churchill would then be less tempted to use the system outside of the President's normal working hours (except in the case of emergencies.)

The first Sigsaly terminal for installation overseas was shipped from New York to London via Scotland on the liner "Queen Elizabeth. The departure was about May 5th or 6th and arrived in the Firth of Clyde near Glasgow on or about May 11th, 1943. The first call placed on the system was made between Washington and London on July 15, 1943. Random key records were delivered by courier and placed in a safe at each remote location with a combination known only to two or three selected officers. On November 26, 1945 a photograph of Churchill's subbasement headquarters appeared in *Life Magazine* (an article starting on page 45) and several engineers at the Bell Labs who had worked on the system were cheered up by recognition of the familiar "Eight Ball" microphone in the telephone on Sir Winston's desk. One of them exclaimed, "Hey! They were actually using it!" From a photograph I saw of the London installation, the electronic equipment (which, of course, was all based on vacuum-tube technology) required a large room filled with about 20 relay racks that reached from the floor to the ceiling, four record turntables, and at least one oscilloscope. The difficulty in moving terminals for the X-System to different locations around the world was recounted by General Dayton Eddy of the Signal Corps who was in charge of "an island hopping series of applications from Manila Bay to Tokyo Bay" during which the equipment was installed in a cement barge. According to him, "the equipment weighed a couple of pounds less than a sawmill."

Applications of the system were carefully shrouded in secrecy. The diligence shown in destroying the random key recordings immediately after use was such that not a single one of those recordings survived the war. The people who built the system often called it "The Green Hornet" because the radio transmissions produced a buzzing sound on ordinary radios that resembled a mad hornet, much like the noise broadcast on a popular children's afternoon radio program of that same name. (Alas, I used to waste time listening to that program myself.) Records captured after the war showed that the Germans were aware of this constant transmission signal and the buzzing noise, but didn't have the vaguest idea what it was for.

Similarly, most messages sent over the system were also cloaked in secrecy and only fragments of a few survived. It clearly was used to coordinate the invasion in Normandy. After Dad's article had been published, a letter was received from a Mrs Dorothy Edghill, wife of Captain Raymond A. Edghill of the 805th Signal Corps, USA.[17] Her husband had been in charge of operating the Sigsaly station in Churchill's underground (sub-basement) headquarters. Edghill was partially paralyzed from a stroke when his wife wrote in May of 1983, but still had a clear memory. He recalled being summoned to set up a "very important phone call" in May, 1944 between Winston Churchill and President Roosevelt. According to the letter, Churchill treated him very cordially. Churchill joked a while about the similarity between their two names and offered him brandy and a cigar. Ray said he would smoke the cigar later and declined the brandy because he was on duty. That didn't stop "Winnie", who continued to sip his own brandy from a glass that had been resting on a table next to his chair. Ray listened to the first part of the conversation in which Roosevelt said, "Hello, Winnie" and Churchill referred to Roosevelt as "Old Pal." Churchill asked about "Falla" and the "Mrs." and

[17] The letter from Mrs. Edghill was mailed on June 1, 1983 and addressed to Dr. Robert Price, a man who had encouraged Dad to write his paper and had done much detective work locating people who had been involved with Sigsaly during he War. (The letter was received long after Dad's article had been published and less than three months before Dad died.)

they talked about the dog for a while and then laughed and joked about "the Dog", noting how important it was. [The underlining was Mrs. Edghill's.] They then went on to talk for a long time about "a surprise attack" to be made at night by moonlight on the 5th or 6th of June, together with various other plans. Ray was asked to set up another conference call a few days later about changes in the plans. Both parties were tense and anxious on that occasion, yet excited. He said they talked about landings on French beaches and various other attacks to be executed. She said that Ray thought the plans were very positive and well organized.

One early message sent back to Washington dealt with an urgent need for replacement antennas on American tanks. After they had landed, they found that the tree branches were so low in Normandy that the tank antennas were being broken off with such rapidity that the entire supply of spare ones had been exhausted shortly after the landing. There is also clear evidence that the system was used in the Pacific to discuss the logistics of delivering the atomic bombs to be dropped on Hiroshima and Nagasaki.

One unanticipated problem was that both Churchill and Roosevelt had initially distrusted the system because they couldn't recognize each other's voices. On July of 1943, the Germans intercepted a call on an insecure line in which Churchill and Roosevelt were discussing the coup in Italy that had just ousted Mussolini's government. Churchill commented, "We do not want proposals for an armistice to be made before we have definitely been approached." Roosevelt agreed. They went on to note that they could safely wait quietly for one or two days and both Churchill and Roosevelt said they would contact "Emmanuel" [the King of Italy] about it personally. The Germans took that to mean that the Allies were up to secret negotiations with Italy. On one occasion in October 1943, rather than use the "X-system", Churchill placed another call to Roosevelt on a military matter over a totally insecure commercial telephone line. He was quickly lectured about the dangers in doing so by the British Secret Service and from the fall of 1943 to the end of the war, it appears that the two leaders used Sigsaly exclusively. (General MacArthur didn't trust the Sigsaly either, but he at least used a secure telegraph system instead.) One of the Sigsaly terminals was carried aboard the U.S.S.Catoctin as far as Sevastapol so that Roosevelt could be in touch with Washington during the Yalta Conference. (Wires were strung on telephone poles for the 50 mile distance from the ship to the Yalta conference locale.) References to Truman's use of the system to talk to Churchill after Roosevelt's death were found in the diary of Fleet Admiral William D. Leahy. At one point Truman had gone over to the Pentagon to use the secret telephone there to discuss Himmler's peace offer with Churchill.

The X-System clearly satisfied its initial goals and the secrecy with which it was guarded probably was far more successful than in any other top-priority military project during the war. Interestingly, the system was entirely developed by a group of highly dedicated civilian electrical engineers, rather than Army or Navy personnel. Ironically, with the advent of the transistor (a later Bell Labs invention) and "Large Scale Integrated

Circuitry" after the war, the whole roomful of electronic equipment at each Sigsaly terminal could be put on a single, small circuit board. One wonders in retrospect how we could have managed during the war without the research and development facilities within the Bell System. The numerous war-time projects completed there ranged from the Proximity Fuse (an electronic device that would cause a shell to explode as it passed near an iron object, even when it had "missed" the target) through advanced Sonar techniques, to a radar-controlled anti-aircraft gun in which an analog computer determined how to fire the gun so as to hit an airplane. What madness it was to have broken up a system that produced what was almost certainly the World's finest physical and electronics research laboratory![18]

[18] The current namesake of the Bell Labs seems to be devoted to making electronic mouse traps! (See the web site: www.belllabs.com)