1000 YEARS OF REVERBS

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WHAT IS REVERBERATION?

DEFINITION OF REVERBERATION

Wikipedia defines reverberation as “the persistence of sound after a sound is produced.”

I like this definition. It isn’t based on the physics of a space, so much as the psychoacoustics.

- The mechanism of the sound being extended isn’t specified, just that the sound persists after the original sound is produced.

Another cool phrase for reverb: “spectral plasma”

REVERBERATION VERSUS ECHOS

- **Both reverb and echoes extend a sound in time, but are perceived differently**
  - Echos are discrete repeats of a sound
  - Reverberation is more of a smear, in which individual repeats are not audible
- **A reverb can consist of thousands of individual echoes, closely spaced together, so that no gaps in the sound can be heard**
- **Reverberance can also be created by randomizing the phases of the individual sine components of a signal**
  - There are no “echoes” per se in this sort of signal, but it sounds reverberant

RT60

- "RT60" is the standard measurement of reverb time
- It is the time required for the reverb signal to decay away to 1/1000th (-60 dB) of the original reverb strength
- RT60 is often measured in different frequency bands
- Acoustic spaces typically have different RT60 rates for different frequencies

EARLY REVERBS: ROOMS, CHURCHES, CONCERT HALLS

CHURCHES AND CATHEDRALS

- **The volume and building materials (stone) of medieval cathedrals resulted in MASSIVE RT60 times**
  - 6 to 9 seconds was common, with some giant cathedrals exceeding 12 second RT60
- **Such a long reverb time would reduce speech comprehension**
  - Chant may have evolved as a way to communicate ideas in a space where individual syllables would be lost
- **Fast musical passages would turn into a blur**
  - (same thing with the Kingdome, for anyone who saw a concert there)
  - Notes would overlap with each other
  - Monophonic phrases would result in perceived polyphony, as notes would hang in the space
  - Music had to be slow and deliberate in a cathedral

CHAMBER MUSIC

- **Chamber music was played in large rooms, that were not as large as concert halls**
  - I should really know the proper names for these rooms…
- **The reverb time of these rooms was usually in the 1 to 1.4 second range**
  - Long enough to increase the spatial perception of the music, but not so long as to blur the notes together in a faster musical phrase

CONCERT HALLS

- Concert halls evolved in tandem with larger symphonic works
- The larger spaces resulted in reverb times between 1.7 seconds and 2.3 or more seconds
- The concert halls that are normally considered to have the best sound have an RT60 in the 1.9 to 2.0 second range
- The reverb time at lower frequencies can be half again as long
- This longer bass RT60 results in a higher perception of spaciousness and envelopment

A BRIEF HISTORY OF ARTIFICIAL REVERBERATION

ECHO CHAMBERS

The idea behind a reverberation chamber (or “echo chamber”) is simple:

- **Send a signal to a speaker**
- **Put the speaker in a room**
- **Put a microphone or two in another part of the room**
- **Mix some of the microphone signal back in with the original signal**

If you want to get fancy, you can aim the microphones away from the speakers, towards the walls, and aim the speaker towards the wall, in order to avoid a direct, non-reflected signal

ECHO CHAMBER HISTORY

Early echo chambers tended to be pre-existing rooms in the studio building

- **Bathrooms worked well, because of the tiles**
- **Concrete stairwells were also popular**
  - The Columbia Records studio in New York had a 7 story stairwell, with a speaker at the top, and microphones on each floor
- **Repurposed existing rooms had sonic isolation issues, and other issues**
  - Having a take ruined by a flushing toilet = no fun

ECHO CHAMBER HISTORY (CON'T)

Dedicated echo chambers avoided the flushing toilet issue, and were designed for optimum sound:

- **Non-parallel walls (a wedge shape was common)**
  - Speaker in the smallest part of the wedge, with microphones on the opposite, large part of the wedge
- **Hard, reflective surfaces for maximum decay**
  - Concrete was used in Capitol Records studios
  - Multiple layers of drywall, covered with plaster, was also commonly used

CAPITOL RECORDS CHAMBERS

ECHO CHAMBER CHARACTERISTICS

- **Fairly high early echo density (due to small room size)**
  - echo density builds with the square of time
- **resonance density scales by the square of frequency**
- **RT60 falls above ~2kHz, due to absorption of high frequencies by air**
- **at 10 kHz, reverb time can't be higher than 1.25 seconds or so**
- **RT60 for concrete chambers can be VERY high at bass frequencies**
  - it was fairly common to EQ this out
  - Abbey Road chambers: output always processed by bandpass filter (low cut at 600 Hz, high cut at 10 kHz)

In some ways, the reverb characteristics of a chamber are similar to a hall:

- long bass RT60
- shorter decay for higher frequencies

ECHO CHAMBER DRAWBACKS

- **An echo chamber takes up a LOT of room in a studio**
- **It isn't just an investment in studio gear - it is an investment in real estate**
  - You can't just buy an echo chamber
- **A chamber needs to be designed, and specially built**
  - A good chamber requires a good microphone, and some sort of speaker
- **The RT60 of a chamber isn't easily adjustable**
  - Usually, the reverb time is fixed by the size of the room and the wall materials
  - Some chambers have been built with variable room size, such as a ceiling that can be raised or lowered

PLATE REVERBERATION

- In 1957, Elektro-Mess-Technik (EMT) released the EMT140 plate reverberator.
- The EMT140 used a thin, cold rolled steel plate, suspended in a steel frame by tight springs
- A driver coil was used to create bending waves in the plate
- One or two pickups were used on the plate to produce output signals
- The result was a high quality reverb, at a much lower cost & size than a reverb chamber
- “only” 600 pounds, 4’x8’x1’

EMT140

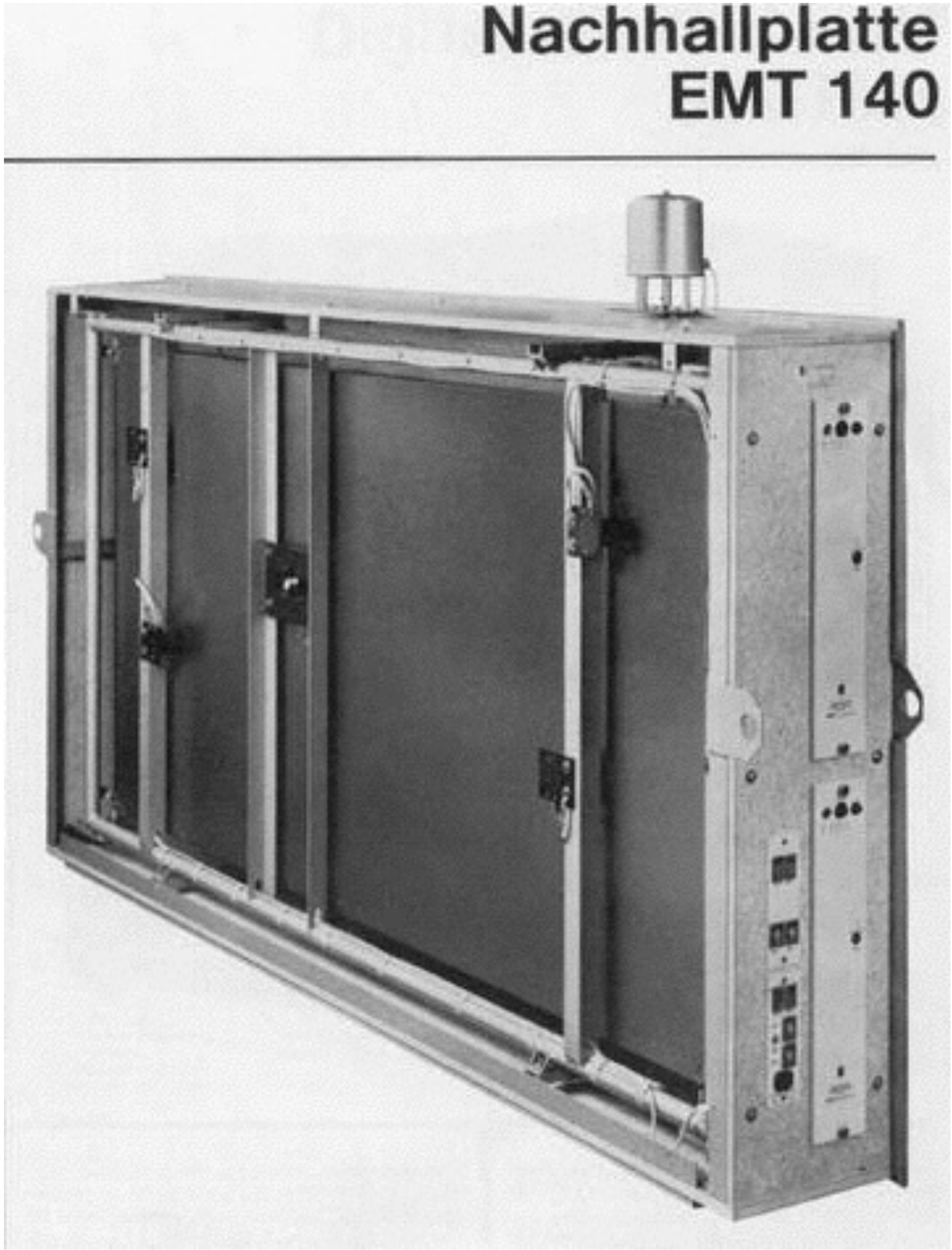


PLATE REVERB DISPERSION

- **dispersion: sound moves faster for higher frequencies**
  - some plates have an audible "whipcrack" or raygun sound (PEW PEW!)
  - some plates don't have as much of this
- **Dispersion affects the stereo imaging**
  - the left and right pickups are different distances from the driver pickup
  - for high frequencies, the pickups may only be a millisecond apart
  - for low frequencies, there can be a difference of 15 or more milliseconds
  - lots of stereo depth generated this way

PLATE REVERB ECHO DENSITY

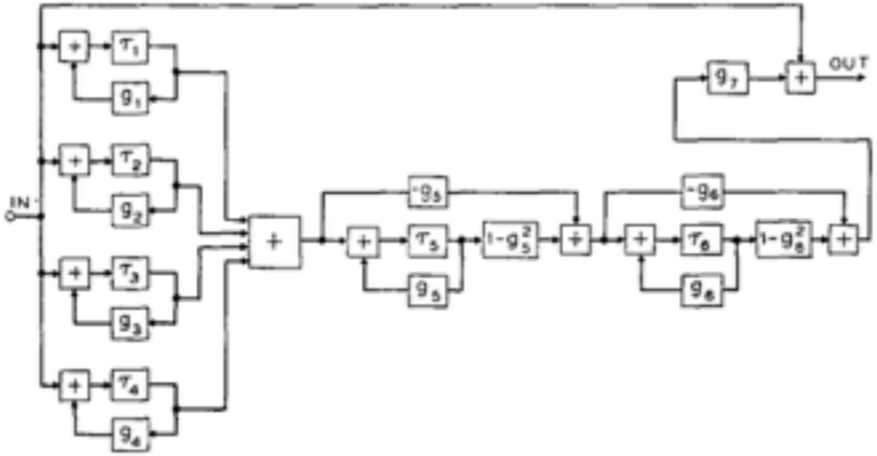
- **echo density builds linearly with time**
- **echo density also builds linearly with frequency**
- **the echos are WEIRD, due to the dispersion**
  - high frequencies move faster than low frequencies, so the impulse is kinda warped
- **by the time the first low echos are heard, the very high frequencies may have had a few dozen echos**
- **the result of this is a sound that essentially has an instant onset of diffuse reverberation**
- **no discrete echos can be heard**

PLATE REVERB: FREQUENCY DEPENDENT RT60

- **RT60 at high frequencies is much lower than the maximum low frequency RT60**
- **when reverb time is adjusted, the lower midrange and low frequency RT60s increase, but the high frequency RT60 stays pretty much the same**
- **for longer decays, this results in a much longer bass RT60, and a short high frequency RT60**
- **this is similar to chambers and concert halls**
- **the cold rolled steel plates used by the EMT140 have a lower high frequency RT60 than stainless steel plates**
    - the Ecoplate reverbs of the 1970s advertised the brighter sound that stainless steel provided in a plate reverb

DIGITAL REVERBS: THE MAINFRAME YEARS

- **In 1961, Manfred Schroeder published 2 papers in the Journal of the Audio Engineering Society, "Natural Sounding Artificial Reverberation" and "-Colorless- Artificial Reverberation"**
- **These papers demonstrated how to add reverberation to digitized signals**
- **The building blocks introduced in these papers are used in digital reverbs to this day**



SCHROEDER REVERB QUALITY

- **Schroeder wrote that the artificial reverberation described in his papers was "indistinguishable from the natural reverberation of real rooms."**
- **This isn't *entirely* true**
- **To modern ears, the Schroeder algorithms sound fairly metallic**
- **This was probably more of a factor of the technical limitations of the day than anything else**
  - Rendering a minute of sound on a mainframe computer would take hours to days in the 1960s
  - The results would then be stored on a magnetic tape, and then driven 30 miles to the facility that had a D/A converter
  - Not a great workflow for iterative tuning of algorithms

DIGITAL REVERB HARDWARE IN THE 1970S

- **Starting in the mid-1970s, dedicated digital reverb hardware became commercially available**
- **The algorithms in these boxes were of higher quality than the Schroeder reverbs**
- **The early pioneers of these reverbs (Barry Blesser, David Griesinger) have discussed how they implemented the Schroeder reverbs on their custom hardware, found them lacking, and were spurred on to improve upon them**
- **Having real-time input/output in hardware sped up the development process**
- **This isn't to say that development was easy**
  - A given digital effects box might have several different processors, each with its own custom assembly language for programming

THE EMT250

Algorithms by Barry Blesser

Released in 1976

Cost: $20K in 1976 dollars!

LEXICON 224

Released in 1979

Algorithms by David Griesinger (& maybe others?)

4 rack units (considerably more compact than the R2D2-esque EMT250)

1970S DIGITAL REVERB BANDWIDTH

- **The EMT250 and Lexicon 224 had lower sampling rates than what we are used to in modern hardware and software**
  - Bandwidth ~8 khz to 10 kHz
  - This is pretty darned dark
  - However, it is a good way to emulate real world spaces, where the high frequency RT60 can't get very high due to air absorption
  - The older digital reverbs had NO energy at high frequencies, so there was no reverb decay up there

1970S REVERB INNOVATION: DELAY LINE MODULATION

- **1970s digital reverbs didn't have much delay line memory available**
  - EMT250: 300 msec
  - Lexicon 224: ~ 1sec
  - This isn't enough to avoid patterns in the reverb decay
- **Delay line modulation used to increase perceived resonance density**
  - think of the resonances as a picket fence
  - by moving the delay lines, it is like taking a photo of a picket fence that is vibrating back and forth
  - the space between the resonances is filled in by the blur
  - this is the idea, anyway.
- **in reality, delay modulation can sound awesome, or can make you seasick if overused**
  - still, a lot of producers and musicians instantly started to exploit the chorusing artifacts of delay modulation
- **Linear interpolation of modulated delay lines leads to high frequency roll off (in 224 and EMT250)**
  - this can create a dull sound, or a more natural sound, depending on how you view things

RIDICULOUSLY LONG REVERB DECAYS

- **The EMT250 had a fairly typical reverb decay in its normal mode: 0.4s to 4.5 seconds**
  - Similar to the EMT140 plate reverb
  - There was also a Space mode in the EMT250 that had a fixed decay of 10 seconds
- **The Lexicon 224 had ABSURDLY long maximum decay times: up to 70 seconds**
  - the high frequency decays can last for tens of seconds, which is something that never occurs in nature
  - this isn't necessarily a bad thing
  - reverbs with super long decay times were quickly adapted to ambient music
  - or, ambient music developed around the use of reverbs with super long decay times

QUANTIZATION NOISE IN REVERBS

- **In the 1970s, 16-bit A/D and D/A convertors were basically unobtanium**
  - The solution was to use 12 bit convertors, with an extra few bits to dynamically scale the levels into the A/D and out of the D/A
  - This was referred to as “floating point” convertors
- **These 12 bit floating point convertors added their own crunchy noise to the signal**
  - The dynamic range was good, but there was more quantization noise for louder signals
- **The 16-bit fixed point processing used inside of these reverbs also added quantization noise**
  - Quantization noise inside of a recursive network, such as a digital filter, will build up
  - A reverb is a HUGE recursive network
- **The end result is that 1970s reverbs had a lot of quantization and truncation noise**
  - This would blur the individual echoes, and create a “thicker” sound
  - Not necessarily a band thing in a digital reverb

DIGITAL REVERBS IN THE 1980S

- **The 1980s were all about digital reverbs**
- **You would here them EVERYWHERE, turned way the heck up in the mix**
  - I’m a reverb developer, and even I have mixed feelings about this…
- **Reverbs were no longer being used simply to smooth out a mix, or to simulate a concert hall. In the 1980s, reverbs were used for a variety of creative applications, both natural and unnatural**

LEXICON 224XL

- Similar to 224, but with 15 kHz bandwidth, new algorithms
- Rich Chamber and Rich Plate were clearer than older algorithms, with more echo density
- no Rich Hall algorithm, for some reason

LEXICON 480L

- Evolved from “Rich” algorithms of 224XL
- Added new RandomHall algorithms
- No chorusing modulation in new algorithms
- Higher sampling rate (44.1/48 kHz), full audio bandwidth, 16-bit convertors
- Still had fairly crusty 18-bit integer math processing

QUANTEC QRS

- The QRS, or QUANTEC-Raumsimulator, was build as a realistic emulation of room resonances
- Higher precision processing than older reverbs, and more delay memory
- The decays and room sizes could range from tiny to infinite

AMS RMX16

- The RMX16 was released in 1981
- The algorithms were original, although I have it on good authority that the AMS folks took a nice close look at one of the first Lexicon 224s in England
- Nonlin reverb: sounded like a gated room reverb (based on drum sound Phil Collins had in early 1980s)

CREATIVE REVERB ALGORITHMS

- The 1980s were swimming in reverbs that left the realms of realism
  - Nonlinear reverbs: lasts for x milliseconds, then is abruptly truncated
  - Reverse reverbs: sounds like recording a reverb, then flipping the tape and playing it backwards
  - Super modulated reverbs used as an effect
  - Shimmer: pioneered by Brian Eno and Daniel Lanois, this used a reverb in a feedback loop with a pitch shifter, to get a reverb that would go up in pitch and harmonic richness as it decayed

1990S TO TODAY

- **As computers have become more advanced, reverb hardware became more and more powerful**
- **For the most part, that power has been used to get more realistic sounds, through brute force**
  - Detailed modeling of early reflections
  - Lots of delay memory for the late tail
- **Examples of modern reverbs:**
  - TC Electronics
  - Bricasti
- **This sound is often better for mixes that sound like they use little or no reverb**
- **There is reverb in there, but used as glue rather than as a special effect, or as a concert hall emulation**

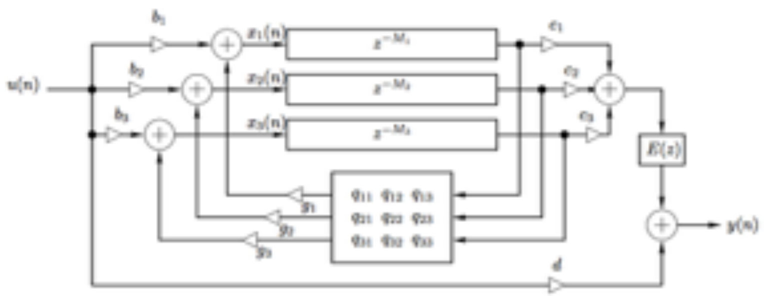
THE REVERB GRIMOIRE

SOFTWARE = SECRECY

- **The workings of physical reverbs were not a mystery**
  - You could walk into the hall, and see how it sounds
  - Or walk into the reverb chamber
  - Or open up the back of the plate reverb box
- **The first software reverbs were published in the JAES and elsewhere**
- **Starting with the first digital reverb hardware (EMT250), the workings of commercial reverbs have been largely secret**
  - Software, inside of custom hardware, isn't easy to reverse engineer
  - Patenting algorithms grants less protection than trade secrecy, if no one can see your code

DIVERGENCE OF ACADEMIA AND INDUSTRY

- **Reverb development has continued to be a subject of academics, at CCRMA, MIT Media Labs, IRCAM, and elsewhere**
- **The main topics of research in academic reverbs are feedback delay networks, convolution, and physical models**



Jot (1991) FDN Reverberator for $N = 3$

- **Commercial reverbs tend to use…something else**
- **WHAT that something else is, isn’t exactly clear, but commercial reverbs usually sound different than academic models**

REVERB ARCHAEOLOGY

- **Figuring out how older commercial reverbs worked is like archaeology**
- **You have some clues, but the people who can tell you what is really going on are either dead (archaeology) or have signed NDAs that prohibit them from talking about it (industry)**
- **You can make guesses, but you might be wrong**
- **However, if you are wrong in an *interesting* way, then the results will still be useful. Or entertaining.**

GETTING IN THE MINDSET OF THE EARLY REVERB GURUS

Growing a beard helps.

READ EVERYTHING

Even though the inner secrets of commercial reverbs haven't been officially published, hints have been dropped.

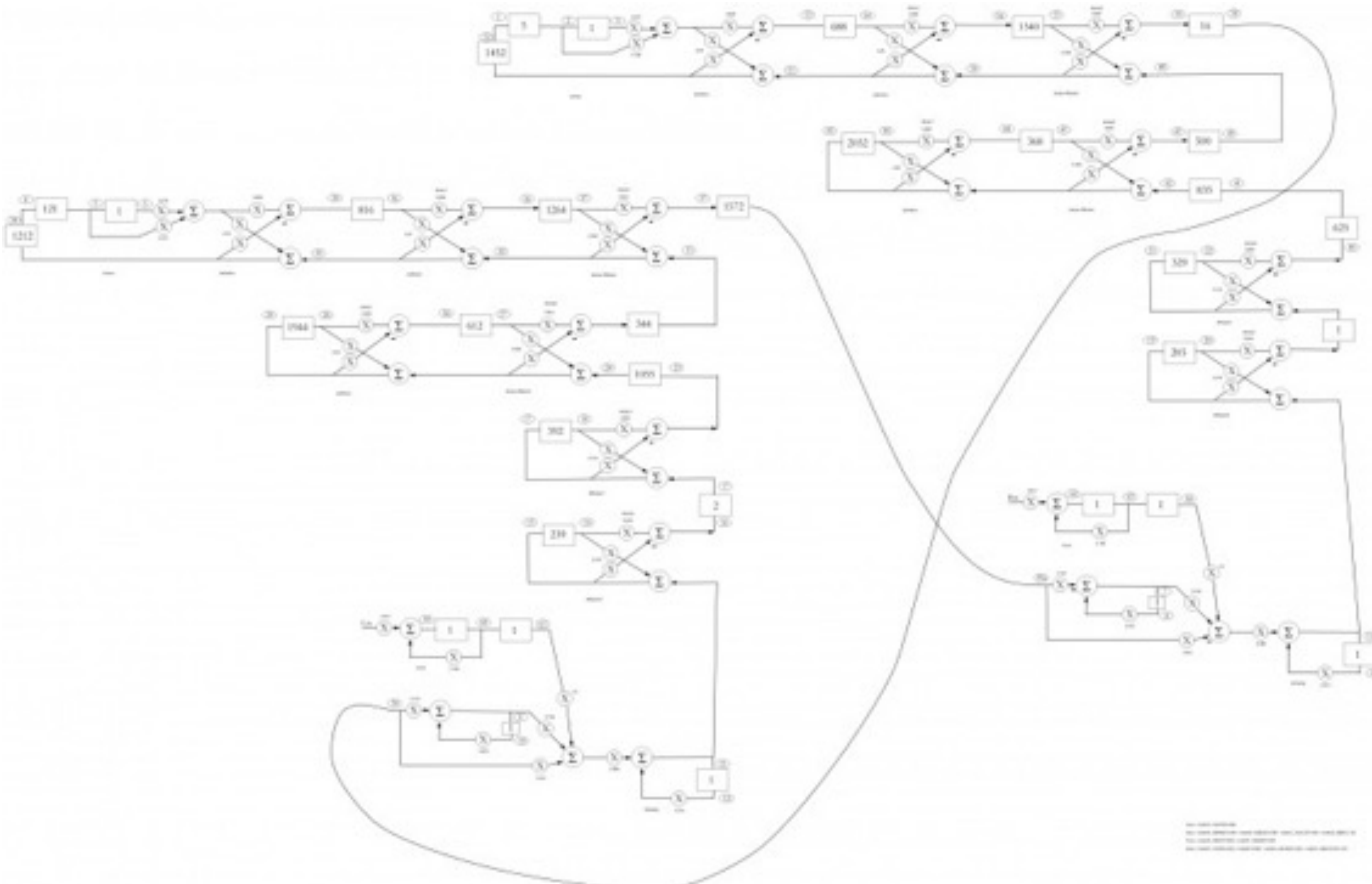
Good places to start:

- Bill Gardner
- Jon Dattorro
- Keith Barr

Learning modern reverb theory is also essential to figuring out, not just *how* the older reverbs worked, but *why* the creators made the choices they did

DATTORRO DROPS HINTS

224XL Concert Hall



DATTORRO DROPS MORE HINTS

“in the style of Griesinger”

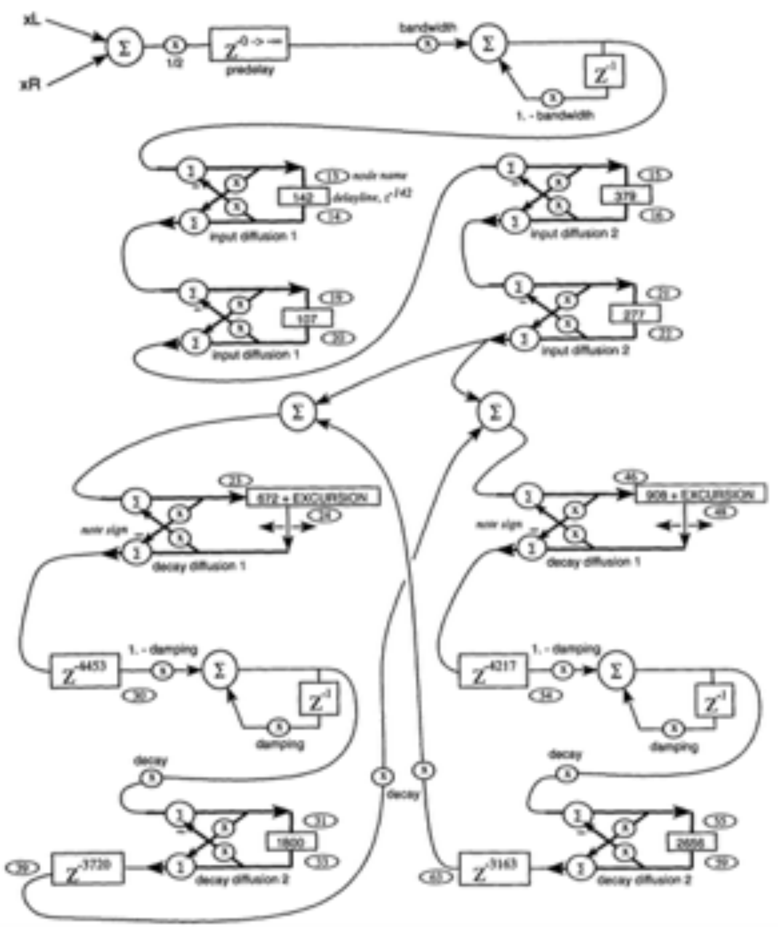
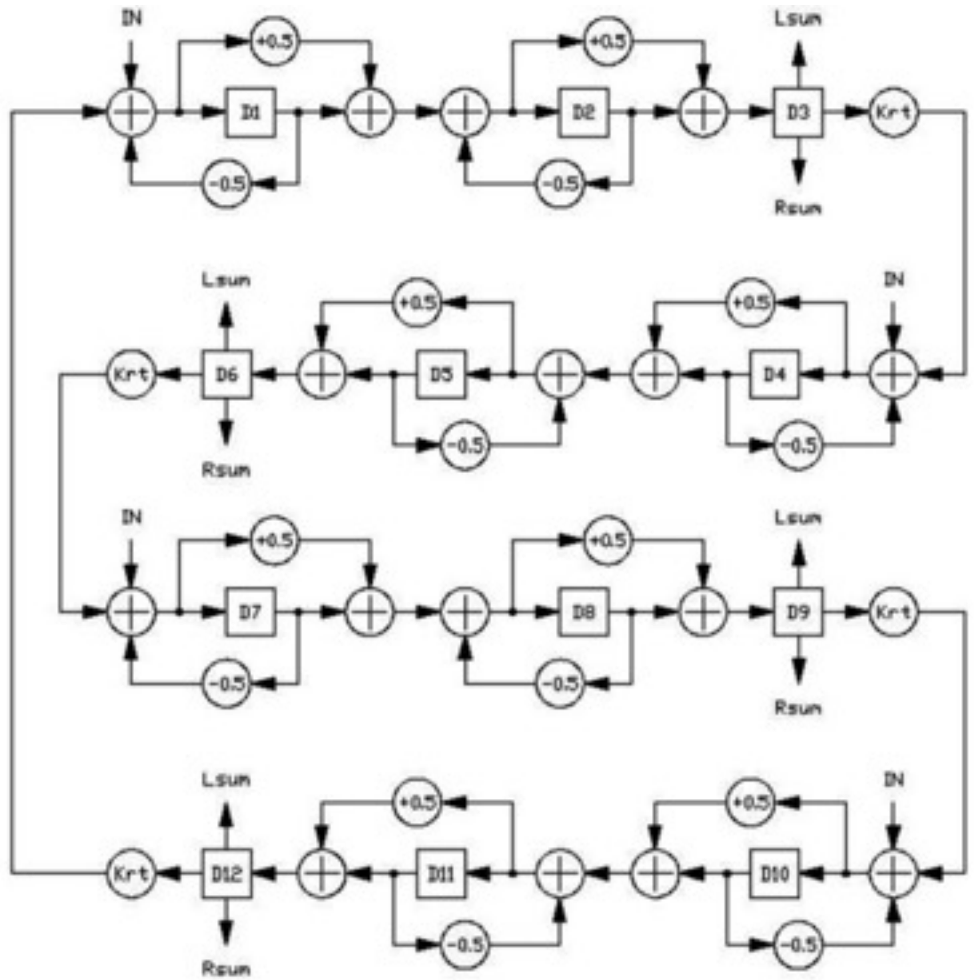


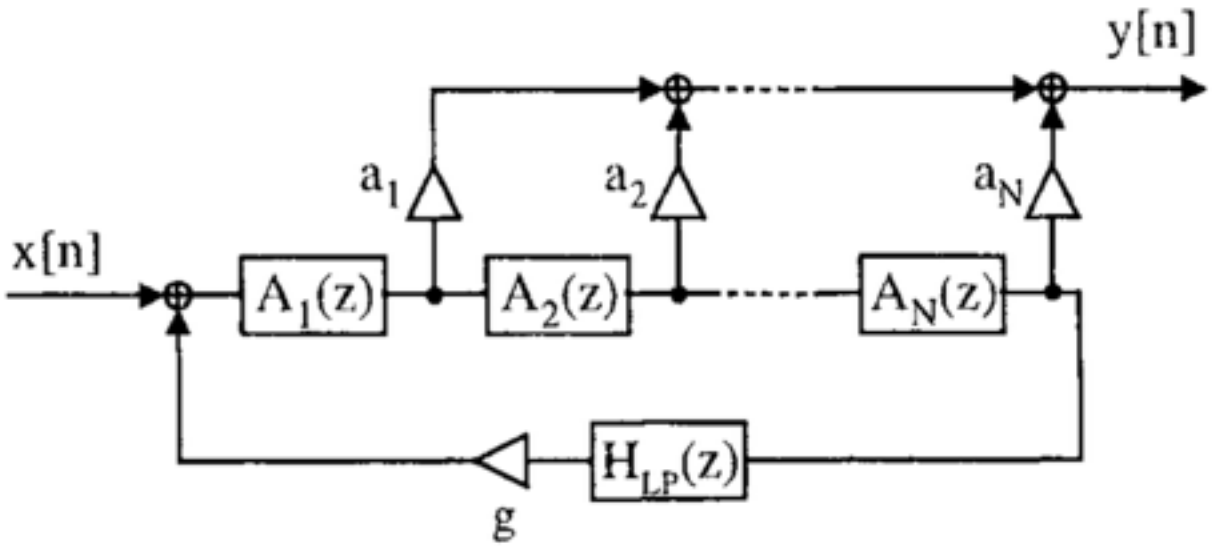
Fig. 1. Simplified plate-class reverberation topology in the style of Griesinger. For output tap structure (y_L, y_R) see Table 2. Delay-line taps at nodes 24 and 48 are modulating.

KEITH BARR DROPS HINTS

"allpass ring"



GARDNER DROPS HINTS



TRY EVERYTHING

- Without implementing an idea, you won't know if it works, or if your understanding of it is correct
- I have written hundreds of reverb algorithms over the past 16 years
- Most of them sucked
- A few dozen were decent
- By learning the theory, you can mix and match techniques as required

MIXING OLD + NEW

- I published a reverb in 2009, that combines techniques from both allpass loops and FDNs
- I've used similar structures in a few of my products, and I like the sound
- Lots of possible variations & extensions to this structure

LISTENING

- Listen to every reverb you can
- Even better: get other people to listen for you, and give you feedback
- Beta testers are essential
- Having several products is even better, as you have more ears on each products, and can improve over time

CAPTURING REVERB HISTORY

- **It would be great to capture the stories of those that worked on the early digital reverberators**
- **Not in order to learn the secret algorithms (those are more fun as secrets)**
- **Instead, it would be great to hear about *how* the early reverb hardware and software was developed, and *why* they chose to make them sound the way they did**
  - What sort of terminal/computer was used to program the early hardware?
  - How long did it take to compile and hear the results?
  - How long was spent tuning a product?
  - How does one get from modeling a concert hall to generating huge slabs of reverb space? Was this intentional, or a happy accident?

THE END

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- **Don Gunn for his review & feedback of the slides, and for setting up the Logic X project I used for demonstrations.**
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Sean Costello

www.valhalladsp.com