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Spectra and Sprites[1]

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New tonality, neo-romanticism, new simplicity, neo-serialism, minimalism, budding Boulezes, miniature Stockhausens, Xenakis copies, neo-impressionists, Donatoni cloning himself… If you looked at concert programme notes or festival brochures, you might think that an entire generation of composers is fixated on the past.

'I don't know what notes to write anymore,' a terribly confused composer told me recently.

'Well, let's write a lot, as many as we can, indecipherable masses for eye and ear,' answer certain people (who would probably want to cover their own tracks).

'Let's limit the number of musical notes as much as possible and repeat them until saturation point,' is the counterattack of some others (who admittedly enjoy an excellent performing rights/fatigue ratio).

'Let's borrow from our predecessors who seemed after all quite satisfied and, if we forget complexes about writing style, we can express ourselves freely,' says the majority (and, in this case at least, with the agreement of music critics).

It is true that after permutating 12 poor notes for three centuries it might seem as if all the combinations had been used up (a small reminder to all you unrepentant serialists: since there are 479,001,600 different possible series, you've still got a sunny future).

Let's forget this dizzying algebra of permutations: we have obviously already heard many of the 'meaningful' combinations of the notes of the tempered scale and, of course, they very often possess connotations, 'tonal' or otherwise. The same could be said about other musical phenomena: rhythm, form, orchestration…

But why do we always have to speak of music in terms of *notes*?

Beyond Categories

Our conception of music is held prisoner by tradition and by our education. All has been cut into slices, put into categories, classified, limited.

There is a conceptual error from the very beginning: a composer does not work with 12 notes, x rhythmic figures, x dynamic markings, all infinitely permutable; he works with sound and time.

Sound has been confounded with its representations, and we work with these, with symbols. Since these symbols are limited in number, we quickly come up against the wall.

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And this situation can become absurd: representations of unbelievable complexity that, in fact, no longer represent anything at all—since the music has become unperformable, or literally unhearable in the sense that there is no correspondence between the music perceived by the listener and that conceived by the composer. No, note and sound are not the same, nor is the note any more the elementary atom of music, nor is it the 'objet sonore' in Pierre Schaeffer's sense. It is only a symbol that gives a more or less precise indication to the performer of what gesture he should make and what result he should try to produce. Therefore all fossilized categories must be abandoned. Why try to distinguish the concept of harmony from that of timbre? The only reason is our cultural conditioning. It is perfectly easy to perceive many distinct frequencies in a single sound (e.g. a low cello note): conversely, we can also perceive a single sound that results from the addition of many frequencies: this is the principle exploited by organ stops. One can progressively separate timbres to create the effect of a harmony and, conversely, progressively fuse harmonic relations until they create a timbral effect. Sometimes with very little change a quite differentiated conglomerate can become a single sonic object, fused. The relative amplitudes of the sonic components, their frequency relations, their quality, make all the difference.

Therefore there is a harmony – timbre continuum. A timbre can be defined as an addition of basic elements, pure frequencies, sometimes white noise bands; a harmony is created by adding timbres together, which is to say the addition of additions of basic sonic components. In other words, there is theoretically no difference between the two concepts; it is all a question of perception, of habits of perception.

In the same way there are other continuums, for instance rhythm/dynamics or rhythm/frequency (since one may descend on the frequency scale until beating occurs), and the continuum formed by the frequency space itself, before being divided into steps.

In fact, why divide this frequency space into octaves in the first place, and then the octave into 12 steps? The only reasons are historical and practical. It is well known that for ages people have tried to divide the octave differently: into 24 (quarter-tones), into 18 (third-tones), sometimes even into wild numbers like Harry Partch. Even 'non-octave space' has been discussed. But finally all this is also arbitrary. And there isn't even a historical justification any more for any such division; micro-intervals are usually just plain painful if they are thought of as extensions of normal octave divisions. Frequency space is continuous and acoustical reality only has to define its own temperaments. If we push this reasoning to an extreme, the combination of pure frequencies could be used to explain all past categories of musical discourse and all future ones. Harmony, melody, counterpoint, orchestration, etc., become outdated and are included in larger concepts. These fundamental elements, these pure frequencies (sine-waves) have their own life, separate, fuse, converge or diverge, and create diverse perceptual phenomena according to their loudness, interrelations, movements…

Of course electronic music destroyed these categorical limits long ago. Electronics opened our ears. But electronic music often suffers from the opposite excess: a lack of formalization, of *écriture* or writing in the largest sense, of structuring the sonic universes that it discovers.

How, in fact, is it possible to organize these infinite sonic spaces that are continuous and unlimited? How to organize the frequency space if all temperament is negated (equal or not), or durations if common ones are not used? Since there are no longer any 'absolute' reference points, it is necessary to fall back on 'relative' ones, and work on differences, on relationships between the elements themselves, and not on the relationship between objects and an external frame of reference. This is the definition of a new kind of music: a 'differential' conception where the interest is in the relationship between objects rather than in the objects themselves, where time is organized by flux and not by segment.

Appearance of Spectra

Musical notation no longer exists as a given, nor as a point of departure; it only serves as the end point of a compositional process and to transcribe the results obtained for the observer (quite often in a necessarily approximate manner).

Establishing links between these elements is a matter of conceiving 'functions' in the mathematical sense. In principle it would suffice to describe the structure of durations and primary partials in order to describe *everything*. In fact this just about describes the process of classical synthesis on a computer.

In the domain of durations, it is easy to organize the appearance of elements in terms of functions (number of elements on the axis, time on the abscissa, or perhaps the number of elements on the abscissa, time on the axis, or even duration on the axis, time on the abscissa). With simple functions, it is possible to generate many types of *rallentandi* or *accelerandi* (more or less exponential, for example); by making them more complex, superimposing and adding functions, one can discover many sorts of fluctuation which can be used to introduce surprise or 'humanize' the process, or to describe patterns of durational organization and disorganization. None of this is arbitrary: instinctive tempo fluctuations made by musicians obey these same laws.

In the frequency domain, which I will consider in a bit more depth, functions are used to construct 'spectra'. A spectrum is a group composed of a certain number of elements, each of which has:

- a frequency (perhaps modulated)
- an amplitude (which can change over time)
- a 'rank' that allows each component to be calculated as a function of the generating sound(s), and may allow the spectrum to evolve over time.

The frequency of each component is therefore defined as: freq = f (rank).

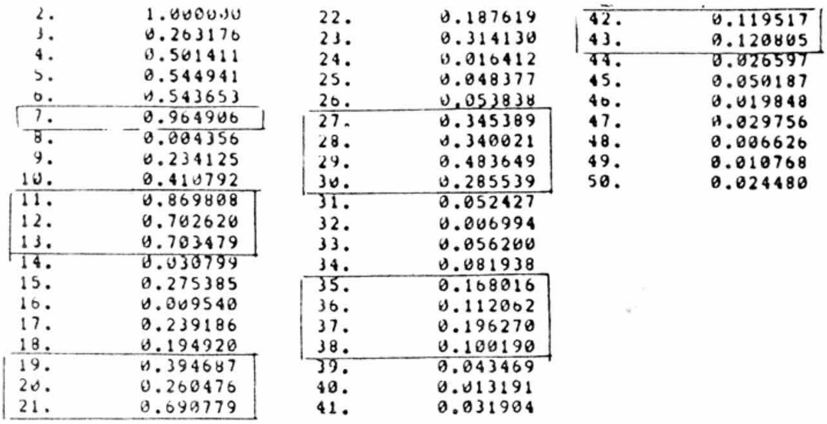
Most known spectra obey a linear relation (y = ax + b). Specifically, the harmonic series has the function: freq = a x r, 'a' being the fundamental, 'r' the harmonic rank. The graph representation of this function is, of course, a straight line stemming from the origin.

In reality, interesting harmonic spectra are not so simple: they are defective, meaning that only certain partials are heard or, put another way, certain are missing. In addition, each component has a relative amplitude. Generally, with instrumental sounds, the lower the partial, the higher the amplitude. But there are many exceptions (that make our orchestra interesting…). Often the second harmonic is stronger than the first (also called the fundamental), or the fundamental may be completely absent, as is the case for low notes on the piano. Also, harmonics are often louder in a certain spectral region, and define a 'formant', which is typical of instrumental timbres.

To construct harmonic spectra, two processes are possible: defining an algorithm or basing it on an instrumental timbre.

Simple waveforms (such as those generated by classic synthesizers) correspond to simple algorithms. For example, 'square' and 'triangle' waves consist only of uneven partials. Pulse waves correspond to defective harmonic series: 1, 2, 4, 5, 7, 8, etc. for a cycle 1/3, 2/3. There is also a function for partial amplitudes: i = f(r). For the partials of a triangle wave, amplitude can be determined by the function $I = l/r^2$ (r still being the ordering), for the square wave: i = 1/r. It is of course possible to construct more complex series by using these basic procedures. One can also 'filter' the harmonic series in many ways, fragment it, only use certain portions, manipulate amplitudes….

Instruments provide a very large number of interesting models that are revealed through spectral analysis. Here, for example, is the spectral analysis of C1 of the piano (the lowest C). The left column indicates partial number, the right relative amplitude (in reference to the loudest partial present). This list stops at the 50th harmonic, but the analysis detects energy up to partial 118 (see Figure 1)!



2.	1.000000
3.	0.263176
4.	0.501411
5.	0.544941
6.	0.543653
7.	0.964906
8.	0.004356
9.	0.234125
10.	0.410792
11.	0.869808
12.	0.702620
13.	0.703479
14.	0.030799
15.	0.275385
16.	0.009540
17.	0.239186
18.	0.194920
19.	0.394687
20.	0.260476
21.	0.690779
22.	0.187619
23.	0.314130
24.	0.016412
25.	0.048377
26.	0.053838
27.	0.345389
28.	0.340021
29.	0.483649
30.	0.285539
31.	0.052427
32.	0.006994
33.	0.056200
34.	0.081938
35.	0.168016
36.	0.112062
37.	0.196270
38.	0.100190
39.	0.043469
40.	0.013191
41.	0.031904
42.	0.119517
43.	0.120805
44.	0.026597
45.	0.050187
46.	0.019848
47.	0.029756
48.	0.006626
49.	0.010768
50.	0.024480

Figure 1 Spectral analysis of the note C1 on the piano.

Many of these principles were used in my work *Désintégrations*, realized at IRCAM in 1982/1983. All of the material for the piece (which is scored for orchestra and tape), its microforms and systems of evolution, were determined from such spectral analyses, from the decomposition or artificial reconstruction of harmonic and inharmonic spectra. Most of the spectra were of instrumental origin: low piano notes, brass instruments, and the cello were used most often.

The tape does not try to imitate instrumental sounds; instead they serve as models for the construction of timbres or harmonies. Many types of spectral treatment are employed in this piece:

- 'Splitting': only one spectral region is used (e.g. the 'bell' sounds at the beginning and end are obtained by splitting a piano spectrum).
- Filtering: to exaggerate or enhance certain partials.
- Spectral exploration: movement within a sound; one hears the partials one by one, timbre becomes melody (e.g. in the third section, small bells made by disintegrating flute and clarinet spectra).
- Inharmonic spectra: 'linear' by adding or subtracting frequencies, 'non-linear' by distorting a spectrum or applying a new frequency curve (e.g. in the penultimate section, progressive distortion of a low trombone sound).

The tape was produced using additive synthesis, which involves the description of all dimensions of each partial. This seemed necessary to allow me to play with each spectrum with the precision that I wished. I had for a long time applied similar techniques to instrumental and orchestral works, and in *Désintégrations* the same processes are found in both orchestra and tape.

Classic synthesis programs were too ponderous and too slow, so the 4X real-time digital synthesizer was used. Even so, each sound required the definition of hundreds of parameters that were calculated by the 'Syntad' program I had written on IRCAM's central computer. The computer was also used in the writing of the orchestral score and in the choice of pitches and calculation of durations. Additionally, 'Syntad' directly generated certain microforms.

Tape and instruments are complementary. The tape often exaggerates the character of the instruments, diffracting and disintegrating their timbre, or amplifying the orchestra. The synchronization between the two must be perfect in performance, which is the reason for the 'click track' that the conductor listens to during the piece.

The piece is made up of 11 connected sections. It progresses from one section to the next by transition-transformation, or by passing a 'threshold'. Each section emphasizes one type of spectral treatment, the description of which is beyond the scope of this article. Suffice it to say that within each type of treatment, each section evolves from harmonic to inharmonic, or vice versa. This creates changes of light and shade accompanied by agitation, and by rhythmic order and disorder.

Let us look at a specific example of spectral treatment, taken from the beginning of *Désintégrations*. The entire opening is based upon aggregates taken from the formants of a low piano spectrum (boxed zones in Figure 1) that serve both for the tape and the instrumental writing. In Figure 2, the aggregates noted ‘a’ come from the spectrum with a virtual fundamental of A#0, aggregates ‘b’ from fundamental C#2 (this relationship between fundamentals is characteristic of bell spectra, explained below). The small numbers correspond to the partial numbers, with notes approximated to the nearest 1/8 tone (a short parenthesis: these procedures for spectral construction always produce ‘non-tempered’ frequencies, which must then be approximated for instrumental performance. For electronic synthesis this problem obviously does not exist and the exact frequencies can be used).

In reality, the piano spectrum is not perfectly harmonic. It contains a slight distortion, which stretches the highest frequencies. This allows us to move smoothly and naturally into the inharmonic domain, for which we have many instrumental models (notably most percussion instruments). Take, for example, the bell: bell manufacturers try especially to obtain a characteristic spectrum that contains inharmonic partials, in particular the minor third over the fundamental (Figure 3).

Electronic music has tried to imitate such sonorities and has usually employed two techniques to achieve this: ring modulation (for analogue synthesis) and frequency modulation (for digital synthesis). In both cases, the relationship between frequency and partial number is linear, as with the harmonic series, but the graph of the function is a straight line that does not pass through the origin. That is the major difference between this type of spectrum and a harmonic series. Figure 4 shows the graph of a typical frequency modulation, whose equation is: freq = c ± (m x i) (m modulator, c carrier, i index).

If the value of ‘i’ is large enough, the frequencies of the equation C − (m x i) eventually become negative. Since a negative frequency is identical to a positive one

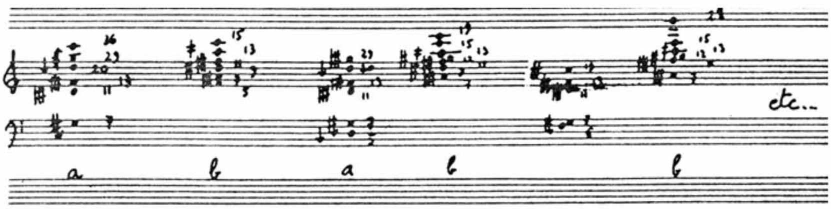



Figure 2 Aggregates taken from the beginning of *Désintégrations*.

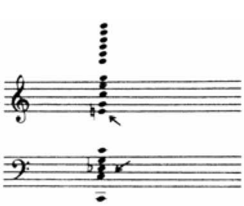



Figure 3 A typical bell spectrum.

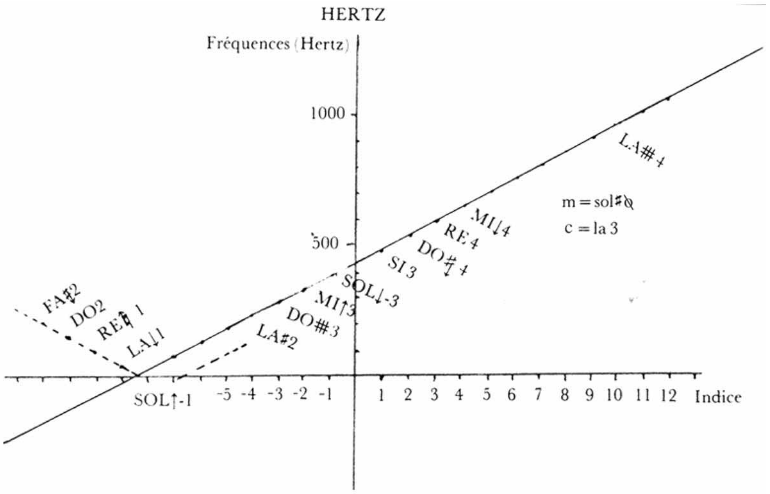


Figure 4 Frequency modulation spectrum. Labeling in this figure uses the French conventions where middle C (C4) is labeled D03; indice refers to the index.

with the phase inverted, the phenomenon of 'foldover' occurs. Indicated by the dotted line, this phenomenon considerably enriches these spectra. The trick is to vary 'i' over time in order to produce spectral fluctuations.

Finally, let's leave the domain of linear functions. The analysis of the piano sound discussed above suggests such a move. The 'real' piano spectrum could be calculated by using a power function ($y = ax^b + c$). If 'b' is close to 1, there will only be a slight distortion in relation to a harmonic spectrum (see Figure 5).

If this phenomenon is exaggerated, eccentric spectra are obtained that have violent compressions or expansions of partials. Figure 6 shows two examples, with $b > 1$ and $b < 1$.

Whatever the nature of the spectrum—harmonic, inharmonic, linear, non-linear—the most important thing is for these spectra to evolve over time: to become more or less rich, enhance their harmonicity or inharmonicity, linearity or non-linearity. This is how musical forms are born—microforms or macroforms—where all is connected and interdependent—frequencies, durations, combinations of frequencies—therefore harmonies and even orchestration. Figure 7 shows a simple example of microform: a collision of high sounds, crotales, glockenspiel, piano, tape—again taken from *Désintégrations*.

All of these sounds derive from harmonic spectra, whose fundamentals will be heard later when they fuse together to create the spectra of a flute, clarinet and muted trombone (doubling instruments that are playing live); the jangling of bells will be reabsorbed by sustained instrumental sounds.

It is harder to give an example of macroform since it would be necessary to analyse an entire section of the piece. In Figure 8 is a small diagram, which corresponds again

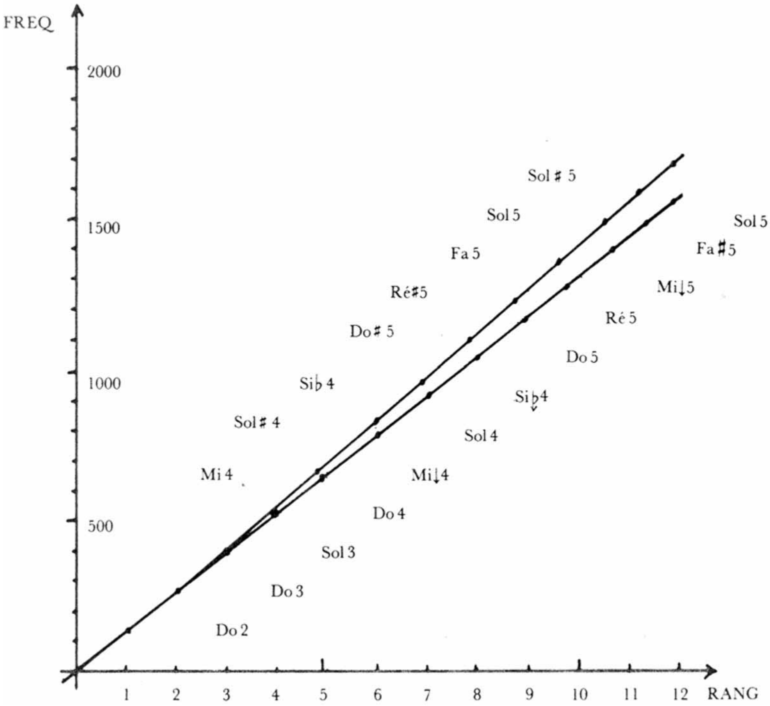


Figure 5 Slight spectral distortion (stretching) relative to harmonic spectrum. Labeling in this figure uses the French conventions where middle C is labeled D03; RANG refers to RANK.

to the end of the same piece, or rather to the section just before the end. The process represented lasts about 3 minutes (though that music also contains many other phenomena).

It should be clear that these compositional procedures demand certain calculations (many calculations in fact): simple calculations for linear functions, much more complex ones for other functions, power, exponential or logarithmic. Moreover, the results of these calculations, expressed in frequency (hertz) or in duration (seconds), must themselves be transcribed into musical notation—a long and tedious process.

This is the first task to delegate to the computer, undisputed champion of repetitive processes: all sorts of calculations, transcription of results, and then visualization—why not—in the form of musical notation, staves, notes and accidentals. The newer microcomputers can define graphic entities that have been attractively named ‘sprites’,[2] which can move around the screen: a good thing for us. Once the result of a frequency modulation calculation, or any other, has been calculated, the screen will fill up with these sprites in the form of musical notes so that we can immediately appreciate the sonic result of our investigations.

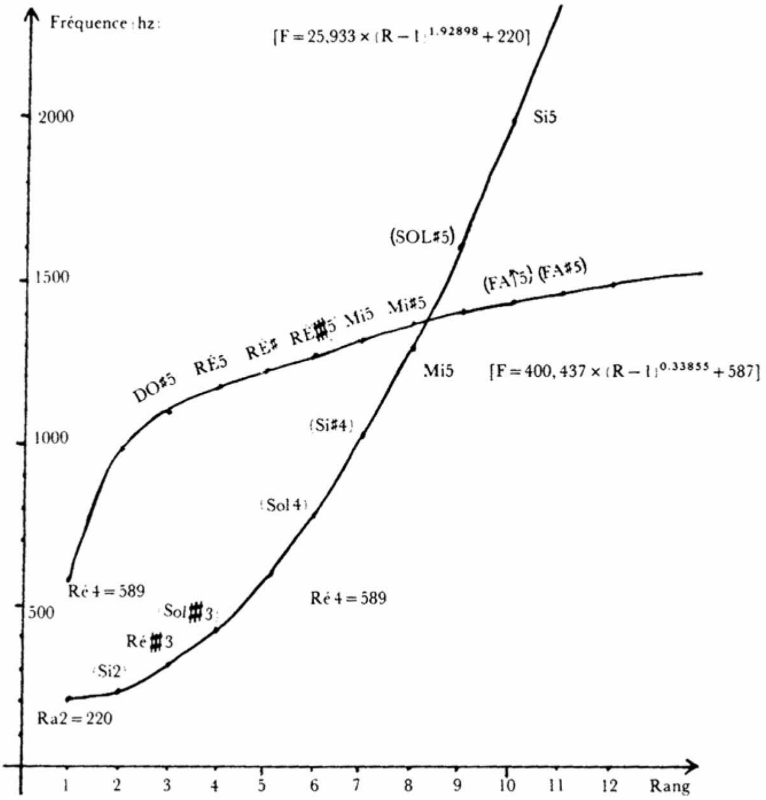


Figure 6 Highly distorted spectra. Labeling in this figure uses the French conventions where middle C is labeled D03; Rang refers to rank.

Data could then be entered quite easily, with a light pen or digitizing tablet or even a piano keyboard. Going a step further: thanks to present interfacing technology and computer-controlled oscillator banks, it is possible to imagine being able to hear these sounds at the same time as they are represented graphically, or to print the results of automated composition algorithms, without needing to use large and costly machines. With 30 or 40 oscillators and the proper software, the (additive) synthesis resources would already be quite powerful and could equal, in speed if not in power, the larger systems found in research institutes. This would be the other role for the computer: a sort of generalized additive synthesis system, capable of generating timbres as well as microforms, macroforms or long evolutions.

Even with such a system, the necessary instructions—the data to enter—are enormous. Moreover, if any attempt is made to generalize some of the previous ideas concerning large-scale form, the system will rapidly become too complex to be understood and controlled in an intuitive manner by the composer/user. Therefore, one must find ways to automate aspects of these processes at an even higher level, to

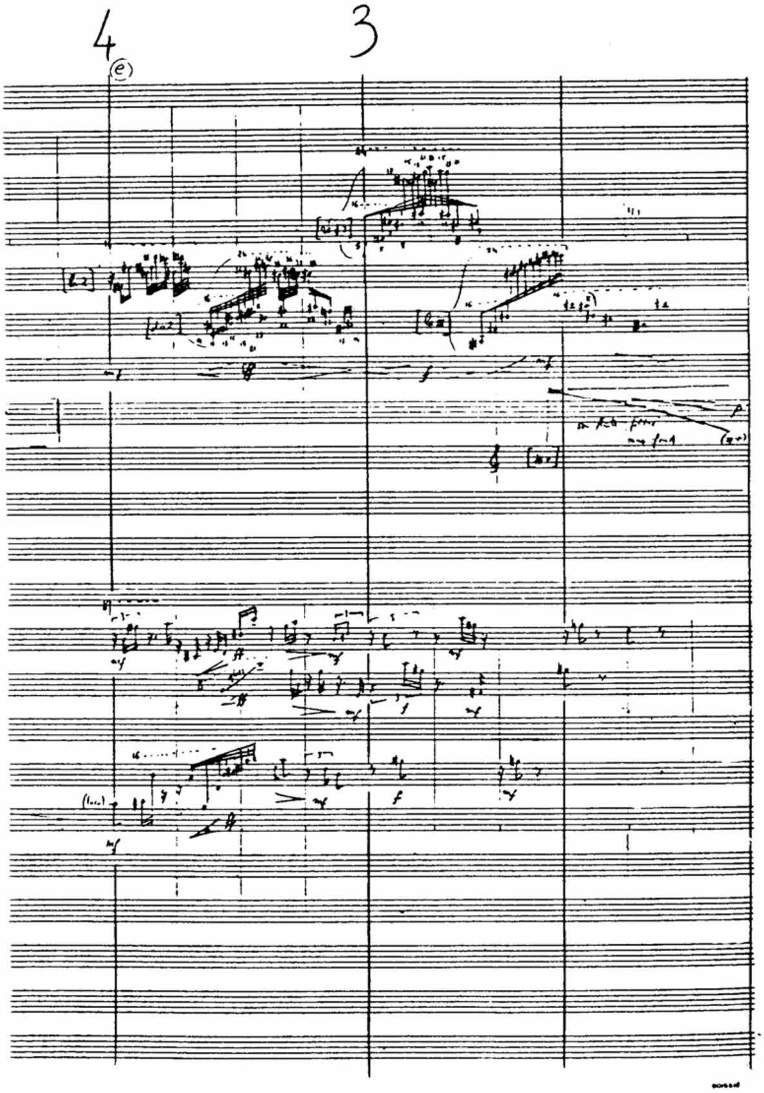



Figure 7 Microform from *Désintégrations*.

build a computer-assisted composition system (CAC). This use of the computer is rather novel; rather than separating sound synthesis on the one hand and automated compositional algorithms on the other, it involves the construction of an interactive, 'inviting' environment—similar to systems that exist in other domains (industrial design, architecture: CAD, i.e. computer-aided design).

The opportunities for the future are staggering. Take the example of orchestration: how can we go beyond the empirical solutions we are presently obliged to use? Obviously, the rules found in treatises are mostly well-founded; the instincts of great

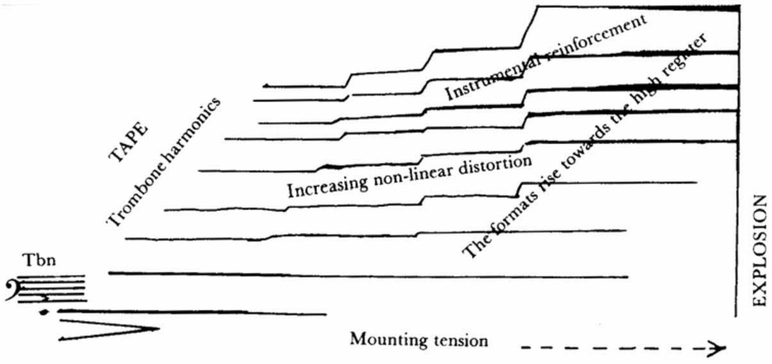


Figure 8 Process immediately preceding the end of *Désintégrations*.

composers have often (though not always) been sure-footed. Nevertheless, couldn't we go even further? We now understand, thanks to acoustical analysis, the solidity and motivation behind many empirical recipes, yet there is still an infinity of new possibilities to discover (I would even say that practically everything remains to be discovered). Ideally, one would have to account for the interaction of each timbre with all others (this is the idea behind 'instrumental synthesis'), implying knowledge of every instrumental spectrum (which all vary depending on loudness, pitch and articulation).

If we wish to achieve the necessary finesse in this work, the use of computers is indispensable, yet again. We need a real computerized orchestration treatise, or rather a CAO (computer-assisted orchestration) system. Even better, we can dream of having 'orchestration machines' in a few years, with which the composer could experiment—all the while listening to the combinations that he imagines.

There is a great future in the alliance of spectra and sprites.[3]

Notes

[1] This article was originally published in English as 'Spectra and Pixies' in *Contemporary Music Review*, 1984, *1*(1), 157–170.

[2] Editor's note: 'Sprite' is a computer-science term used to refer to small bitmap images that were often used in videogame programming in the 1980s; the term can also sometimes refer to icons. In general, the rise of font-based programming and the exponential increase in computing and graphical power of modern computers have made sprites (and other techniques intended to reduce the computing power required for a given task) less important to the actual work of programmers in the 23 years since this article was written. This change does not alter the nature of the relationships described, only the technical means that would now be used to realize them.

[3] Editor's note: This article was originally published in 1982. Since that time, many of the systems imagined have been created at IRCAM and elsewhere. Some of this work is mentioned in later articles. Additionally, a computer-assisted orchestration system related to the one described here is currently under construction at IRCAM.