A classification of electronic signal-processing functions

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Abstract—**A new classification of electronic signal-processing functions is proposed. Electronic signals can either be 1. generated, 2. dissipated, 3. transformed, 4. replicated or 5. combined. Of these five classes of signal-processing functions, only the transformer and the combiner can be further subdivided into three function subclasses, being *a*. translation, *b*. expansion and *c*. discrimination. Since signals can undergo these actions either in *i*. the time domain, *ii*. the frequency/phase domain or *iii*. the magnitude domain, we finally arrive at 1 + 1 + 3 + 9 + 9 = 23 elementary electronic signal-processing functions. Well-known examples of elementary electronic building blocks are classified. New elementary building blocks are defined, among which the "phaser," the "spreader" and some that do not have a name as yet.**

I. INTRODUCTION

Electronics, by definition, is the science of manipulating electrons. These electrons are tiny yet powerful quanta that carry energy from one place to another forming an electrical current or store energy on one place thereby creating a voltage. Manipulation of the electrons is done by means of active components, such as transistors and radio tubes, grouped together in electronic circuits. Sometimes, the aim of the electronic circuits is to manipulate the energy itself, e.g., to make it suitable to be used as an energy supply, preferably without severe energy loss. Another time, the manipulation by the electronic circuits is done on the fluctuations of the energy carried by the electrons, called signals. These fluctuations then represent information, which must be preserved, thus without severe information loss. Electronics therefore deals with both energy processing and signal processing.

Browsing through the extensive literature on electronics in general and electronic design in particular, the reader is often confronted with a large variety of electronic signal-processing functions, which are treated phenomenologically instead of systematically. For instance, in [1] the associated circuits are categorized as subsequently amplifiers, filters, signal sources, waveshaping circuits, digital logic functions, digital memories, power supplies, and converters.

In many textbooks, intended for freshman courses on electronics, such a categorization is not mentioned explicitly or not present at all. Usually, these books start with a description of the transport, generation and recombination mechanisms of the minority and majority carriers in semiconductors, eventually leading to a networktheoretical description of the most important semiconductor devices, being the diode, the bipolar transistor and the field-effect transistor. Inevitably, the next chapters then subsequently discuss linear circuits, diode circuits, single-transistor circuits, operational amplifiers and negative-feedback amplifiers. Often also filters, switches or some elementary transistor circuits, such as the differential pair and the current mirror, are presented. Some books additionally give some examples of electronic systems, in which the elementary building blocks that have been introduced in the previous chapters play a important role.

However, in most cases the Author has come across, throughout these books, the emphasis was on *analysis* of the primary behavior of a particular electronic circuit and its imperfections caused by second-order effects rather than on the *design* of these circuits with predefined functionality and quality. This gives the reader, which often is a student, the impression that electronic design is an art rather than a technique — which is paradoxical, since the word “technique” originates from the Greek word $\tau\eta\chi\nu\eta$, which apart from “technique” also means “art.”

This became apparent to the Author when he was asked to take over a course on Analog Electronics as part of the curriculum of Industrial Design Engineering (IDE) at Delft University of Technology. The course had already been given to IDE students for several years, but was considered by the students difficult to pass. One of the main reasons for this, as it appeared clearly from interviews with students, was that only at a very late stage it became clear to them how a carefully organized combination of electronic components could indeed lead to an improvement, seen from an application point of view. While the desired application is always there first; the eventual solution follows afterwards. From that moment on, the course starts by first defining information, signals and signal processing, and is then continued by a description and examples of transducers and elementary signal-processing functions. The course proceeds by subsequently discussing passive filter networks, negative-feedback opamp-based amplifiers, diodes, power supplies, transistors, IC technology and oscillators. As a vehicle throughout the whole course, a television receiver is chosen. One of the educational objectives of this course is that the student knows how to analyze a TV in terms of transducers and elementary signal-processing functions. Another educational objective is that the student knows how to design one of the amplifiers and a sawtooth generator as used in a TV.

Two years ago, after the retirement of an older colleague and following a internal workshop on the new electronics curriculum, the Author was asked to give a similar course to freshmen in Electrical Engineering (EE). Also this course, albeit more advanced, starts with a classification of electronic signal-processing functions. It is the outcome of this renewed focus on *electronic design*, which has finally led to this paper.

In the following section, electronic signal-processing functions are first divided into five classes and three subclasses based on the amount of input and output signals and their input-output relation. Section III focuses on the domains and ranges of these signals, followed by a comprehensive list of elementary electronic signal-processing functions in Section IV. The list comprises, next to definitions, also many examples of well-known circuits. Some new elementary building blocks are identified.

II. CLASSES OF ELECTRONIC SIGNAL-PROCESSING FUNCTIONS

In this section, we concentrate on the amount of electrical signals involved in electronic signal-processing circuits and their relation. Electrical signals at the input, i.e., going into an electronic circuit, can be either

- **absent**, i.e., the amount of input signals equals zero, or
- **single**, i.e., the amount of input signals equals one, or
- **multiple**, i.e., the amount of input signals is greater than one.

Likewise, electrical signals at the output, i.e., coming from an electronic circuit, can be either absent, single or multiple. Electronic circuits thus generate zero, one or more than one electronic output signal out of zero, one or more electronic input signals. In principle there are thus $3 \times 3 = 9$ classes of signal-processing functions. However it can readily be proved that four of these can be composed by means of two of the remaining five and are thus superfluous. The latter five classes of signal-processing functions subsequently are (see Figure 1):

1. **Generation**, i.e., one electrical output signal is created without any electrical input signal,
2. **Dissipation**, i.e., one electrical input signal is going in, but no electrical output signal is created,
3. **Transformation**, i.e., one electrical output signal is created out of one different electrical input signal,
4. **Replication**, i.e., more than one equal electrical output signal is created out of one electrical input signal, and
5. **Combination**, i.e., one electrical output signal is created out of multiple electrical input signals.

In the sequel, for the sake of clarity, we will discuss the combiner and its derived functions as having only two instead of multiple input signals. One of these input signals will often be

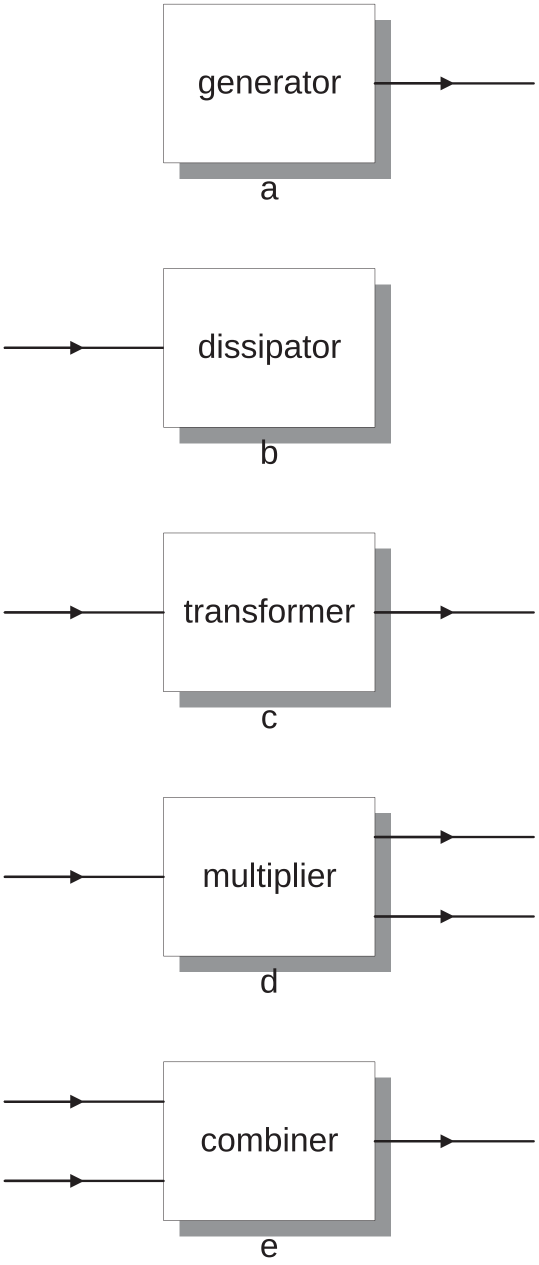

Fig. 1. The five classes of signal-processing functions: *a*. generation, *b*. dissipation, *c*. transformation, *d*. replication and *e*. combination

referred to as *the* input signal, whereas the other will be referred to as the *control signal*. In case of more than two input signals, the definitions and related discussions can readily be generalized to incorporate their influences as well.

A description of the generator, the replicator and the dissipator is, of course, rather straightforward. A careful consideration of the transformer and the combiner, however, learns that their functions can be further subdivided into three function subclasses, being:

a. Translation, i.e., the signal domain and range are congruent and the relation between input and output signals can be written as an affine expression. In other words, the output signal is a shifted version of the input signals and possibly an internal reference.

b. Expansion, i.e., the signal domain and range are not congruent, and the relation between input and output signals can be written as an non-affine, thus either strictly linear or non-linear, expression.

c. Discrimination. i.e., the relation between signal domain and range can be written in the form of a Boolean expression. In other words, a distinction is made based upon the input signals themselves and possibly an internal reference.

Before we split the above classes and subclasses of signal-processing functions into their elementary signal-processing functions, it may be illustrative to give two examples.

The first example is one that illustrates an **expanding transformer**, which, according to the above definitions, thus should have one input signal and one output signal and their relation could be written as an non-affine, thus either linear or non-linear, expression. This is the case for, e.g., an *amplifier*. Amplification is an indispensable function in almost any electronic system. The aim of an amplifier is to bring the information that is offered at its input by the source to a higher energy level, available at its output to the load. Its ideal transfer function is that of a linear magnitude transfer function, which can be written in an analytic form as

$$y = k \cdot x \tag{1}$$

x, y and k being the input signal, the output signal and the constant gain factor, respectively. Note that also an *attenuator*, the antipole of an amplifier, falls into the subclass of an expanding transformer, albeit that one would rather denote an attenuator by the term compressing than expanding since its range is smaller than its domain.

The second example is one that illustrates an **expanding combiner**, which, according to the above definitions, thus should have multiple input signals and one output signal and their relation could be written as an non-affine, thus either strictly linear or non-linear, expression. This is the case for, e.g., a *controlled* *amplifier*. Controlled amplifiers are widely used in communication systems. They can be found in e.g., mobile phones, radio receivers and audio amplifiers. The aim of a controlled amplifier is to adapt the dynamic range of the signal that is offered at its signal input by the source to the dynamic range of the signal that is needed at its output by means of a control signal. Its ideal transfer function is that of a controlled magnitude transfer function, which can be written in an analytic form as

$$y = f(x_2) \cdot x_1 \tag{2}$$

x_1, x_2 and y being the input signal, the control signal and the output signal, respectively. A popular realization of a controlled amplifier is a *multiplier*, often embodied by a four-transistor translinear loop [2]. Its magnitude transfer function ideally equals

$$I_y = I_{x_2} I_{x_1} / I_{\mathrm{ref}} \tag{3}$$

I_{x_1}, I_{x_2}, I_y and I_{ref} being the two input signals (both electrical currents), the output signal (also a current) and a reference current, respectively.

III. ELECTRONIC SIGNALS

Now that we have defined classes and subclasses of signal-processing functions and before we further subdivide these into the 23 elementary signal-processing functions, we first consider the nature of electronic signals. Electronic signals are functions of a variable, which is often either **time** or **frequency**. The domain $\mathcal{D}$ of a signal is a subset of the real time or frequency. The **magnitude** of a signal or, also correct, the signal itself may take values in any set $\mathcal{R}$, called the signal range. Many electronic signals may be expanded as a finite or infinite linear combination of harmonic signals, which, in turn, can be described by

$$x(t) = ae^{j\omega t} = \alpha e^{j\phi} e^{j\omega t} = \alpha e^{j\omega t + \phi} \tag{4}$$

with a a complex constant called the complex amplitude, α the magnitude, ω the angular frequency, ϕ the initial phase of the signal and t the real time, respectively. Electronic signals are thus characterized by the three quantities

i. Time,
ii. Frequency or phase, and
iii. Magnitude

IV. ELEMENTARY SIGNAL-PROCESSING FUNCTIONS

Since there are five classes of signal-processing functions, being generation, dissipation, transformation, replication and combination, of which two can be further subdivided into the three sub-classes translation, expansion and discrimination, and further generation, transformation and combination can take place in the time, frequency/phase or magnitude domain we can identify the following 23 *elementary signal-processing functions*:

1. **Dissipation.** A dissipating circuit element transforms an electrical input signal into a non-electrical phenomenon, often heat. Its electrical output signal y thus can be written analytically as: $y = 0$. As an example we mention a resistor connected in parallel with a capacitor in electronic power supplies, often called a "bleeder," whose only function is to discharge the capacitor when the circuit is switched off. It seems somewhat overdone to indeed call dissipation a signal-processing function. However, the same argument should hold for the upcoming two, being replication and generation, which are often indeed shared among signal-processing functions.

2. **Replication.** A replicator makes (multiple) copies of the input signal. Its transfer function can be written as: $y_i = x$, x and y_i being the input signal and the i output signals, respectively. A well-known example of an electronic replicator is a *current mirror* with multiple outputs.

3. **Generation of time.** A time generator produces an output signal of fixed duration by means of an internal time reference. Its output signal can be written as: $y(t) = f(\cdot)$. As an example we mention a *monostable multivibrator*, or simply *monoflop*, a circuit that produces a pulse each time the circuit is triggered. In many hotel corridors the light switches contain monostable multivibrators. When the button is pushed the light turns on, stays on for a few minutes and then automatically turns off.

4. **Generation of frequency.** A frequency generator, or *oscillator*, produces a harmonic output signal by means of an internal frequency reference. Its output signal can be written as: $y(\omega) = f(\cdot)$. Many examples of oscillators can be found in electronic systems. For instance, a television receiver contains several oscillators. One oscillator generates a ramp waveform of about 16 kHz that is used for the horizontal movement of the

electron beam in a picture tube. A second oscillator generates a 50 or 60 Hz ramp waveform that is used to produce the vertical scan. Another oscillator generates a sinusoid at about 4 MHz that is needed for retrieving color information from the received signal. Still another oscillator, called the *local oscillator*, generates a sinusoid that is used to select the channel of interest.

5. **Generation of magnitude.** A magnitude generator, or *dc source*, produces a constant output signal by means of an internal magnitude reference. Its output signal can be written as: $y = k$, k being a real constant. A well-known example is the *bandgap reference* that generates a nearly constant voltage over wide temperature and supply voltage ranges by means of a linear combination of multiple base-emitter voltages. DC sources are often applied in *power supplies*, but also in *analog-to-digital converters*, *comparators* and *level shifters*.

6. **Constant translation in time.** A time shifter, or *delay*, reproduces the input signal at its output after a fixed time interval. Its transfer function can be written as: $y(t) = x(t - t_0)$, t_0 being the delay time. A well-known implementation of a time shifter is a *delay line*, often implemented by a *transmission line*.

7. **Constant translation in frequency.** A frequency shifter, or *frequency converter*, reproduces the input signal at its output at a different frequency. Its transfer function can be written as: $y(\omega) = x(\omega - \omega_0)$, ω_0 being the frequency shift. Frequency conversion occurs in almost any receiver or transmitter system and is often facilitated by means of a local oscillator (see above) and a *mixer*. Its necessity often stems from the fact that the frequency at which the transmission and reception take place, the carrier frequency, is much higher than the frequency at which other elementary signal-processing functions can successfully be implemented. The implementation of the mixer is always, in essence, based on the mathematical multiplication of two input signals. Usually one of these signals is a sinusoidal waveform produced by a local oscillator. Frequency conversion of an input bandpass signal, centered around ω_c, by a mixer and a local oscillator that delivers a sinusoid at ω_0 then yields two output bandpass signals, one at the up-conversion frequency band, centered around $\omega_c + \omega_0$, and one at the down-conversion band, centered around $\omega_c - \omega_0$.

8. **Constant translation in magnitude.** A magnitude shifter, or *level shifter*, reproduces the input signal at its output at a different value. Its transfer function can be written as: $y = x - x_0$, x_0 being the level shift value. Level shifters are often found in electronic circuits to facilitate correct biasing of these circuits, i.e., that the correct values of voltages and currents are present at the transistors' input and output terminals. They are implemented by floating *voltage sources* and grounded *current sources*.

9. **Constant expansion in time.** A time expander, or alternatively a time compressor, reproduces the input signal at its output on a different time scale. As an example of expansion in time by means of an analog system, in this case inevitably accompanied by a time delay, we mention the playback of a tape recording at a lower transport speed. Compression in time, for instance, occurs when reading out a digital *shift register* at a higher clock speed than used for loading. This is applied in today's GSM phones to accommodate the *time-division multiple-access* (TDMA) scheme.

10. **Constant expansion in frequency.** A frequency expander, or alternatively a frequency compressor, reproduces the input signal at its output on a different frequency scale. As an example we mention the same playback of an analog tape recording at a different transport speed. This clearly indicates how time and frequency are interwoven. Another example of a frequency expander is a system that is used for long-distance radio communication and is called a "repeater." A repeater receives a weak signal in a certain frequency band and instantaneously transmits it at a larger power level in a different frequency band. A nonlinear transformation that also yields an expansion in frequency occurs in a (frequency-) *controlled oscillator*, as, e.g., used for the generation of frequency-modulated (FM) signals.

11. **Constant expansion in magnitude.** A magnitude expander, or *amplifier*, reproduces the input signal at its output at larger values. Alternatively, a magnitude compressor, or *attenuator*, reproduces the input signal at its output at smaller values. The function of an amplifier has already been discussed in Section II.

12. **Constant discrimination in time.** A time discriminator, or *switch*, reproduces the input signal at its output only at certain

time instants or intervals. Its transfer function can be written as: $y(t) = x(t)$, $\forall t \in \mathcal{T}$, $y(t) = 0$ otherwise, $\mathcal{T}$ being a fixed subset of the real time t for which the input signal should be passed to the output. A good example of a switch is an ordinary light switch or a *timer*.

13. **Constant discrimination in frequency.** A frequency discriminator, or *filter*, reproduces the input signal at its output only at certain frequencies or frequency bands. Its transfer function can be written as: $y(\omega) = x(\omega)$, $\forall \omega \in \Omega$, $y(\omega) = 0$ otherwise, Ω being a subset of the real angular frequency ω for which the input signal should be passed to the output. Next to amplification, also filtering is an indispensable function when it comes to the design of electronic systems. In practice, a piece of electronic apparatus, which does not contain at least one rudimentary filter, can hardly be found. Electronic filters are, e.g., used for channel selection in radio or television receivers, for noise and interference suppression in communication transceivers and in audio *equalizers*.

14. **Constant discrimination in magnitude.** A magnitude discriminator delivers some function of the input signal at its output only for certain signal levels. Its transfer function can be written as: $y = f(x)$, $\forall x \in \mathcal{X}$, $y = 0$ otherwise, $\mathcal{X}$ being a subset of the signal domain $\mathcal{D}$ for which the input signal should be passed to the output. An example of a magnitude discriminator is a half-wave *rectifier*, in its simplest version implemented by a single ideal diode. When the anode-cathode diode current is positive, the diode is said to be forward biased and the input voltage appears at the output. However, when the anode voltage becomes negative with respect to the cathode, the diode becomes reverse biased and the output voltage no longer follows the input voltage but remains zero. Magnitude discriminators can be identified in *level detectors*, *limiters*, static *wave shaping circuits*, *logic circuits* and most *power supplies*.

15. **Variable translation in time.** A variable translation in time, or variable delay, reproduces the input signal x_1 at its output after a variable time interval that is a function of the electronic control signal x_2 applied at the second input terminal. Its transfer function can be written as: $y[t] = x_1[t - \Delta t(x_2)]$, Δt being the delay time, which itself is a function of the control signal x_2. The variable delay does not play an important role in most electronic systems. However, it is the main signal-processing block in an audio device that is sometimes used by musicians that play the electrical guitar: the *phaser*. A phaser produces a sound that is close to that of a “wah-wah,” a “flanger,” a “chorus” or a Lesley box and enriches the plain sound of the electrical guitar. Especially when following a “distortion” or “fuzz” the result could easily tempt one to consider oneself to be a new Jimi Hendrix. In line with the nomenclature used for musical instruments we call this variable delay a phaser.

16. **Variable translation in frequency.** A variable translation in frequency, or variable frequency conversion, reproduces the input signal x_1 at its output at a variable different frequency that is a function of the electronic control signal x_2 applied at the second input terminal. Its transfer function can be written as: $y[\omega] = x_1[\omega - \Delta\omega(x_2)]$, $\Delta\omega$ being the frequency shift, which itself is a function of the control signal x_2. Variable frequency converters are found in electronic receiver tuners, multi-channel transmitters and in communication systems that use *frequency hopping* to provide simultaneous use of a wide frequency band by many users via *code-division multiple access* (CDMA) or *spread-spectrum* techniques. They are often implemented by means of a local controlled oscillator (see above) and a mixer. In line with this terminology we adopt the name *spreader* for this elementary signal-processing block.

17. **Variable translation in magnitude.** A variable translation in magnitude occurs everywhere an *addition* or *subtraction* takes place. The resulting output signal thus can be written as: $y = x_1 \pm x_2$, x_1 and x_2 being both input signals. Voltages can be added or subtracted by connecting voltage sources in series or anti-series; currents are readily added or subtracted by connecting current sources in parallel or anti-parallel. In fact, electronic circuits are not needed for these operations. If present, they merely serve to buffer, copy or invert the electronic signals. Addition and subtraction are omnipresent in electronics circuits. There are not many electronic circuits that do not comprise at least one addition or subtraction.

18. **Variable expansion in time.** A variable expansion in time should reproduce the input signal at its output on a different variable time scale. To the best of the Author's knowledge, the variable time expander does not play an important role in today's electronic systems. Its functionality can, however, be found in specific (digital) audio signal processors, called "sequencers." The interested reader is referred to the open literature or the many web pages on this subject. Another example, though in practice not strictly performing a variable expansion in time, is a well-known pulse modulation scheme, being *pulse width modulation* (PWM). In this scheme the duration of a pulse becomes a function of a modulating input signal.

19. **Variable expansion in frequency.** A variable expansion in frequency, though often not recognized as such, is what happens, e.g., in many continuous-envelope modulation schemes that do not modulate an oscillator itself but perform a modulation on the outcoming oscillator signal. This is often the case for BPSK (binary phase shift keying) and other *phase modulators*. Also *pulse density modulation* (PDM), in which the amount of pulses that is passed to the output in a certain time interval depends on the modulating signal, belongs to this elementary signal-processing function.

20. **Variable expansion in magnitude.** A variable expansion in magnitude, the function of a *controlled amplifier*, can be expressed analytically as: $y = f(x_2) \cdot x_1$. The controlled amplifier has already been discussed in Section II. Ordinary *amplitude modulation* and *pulse amplitude modulation* (PAM) are often realized by means of controlled amplifiers.

21. **Variable discrimination in time.** A variable time discriminator, or *controlled switch*, reproduces the input signal at its output only at certain variable time instants or intervals. Its transfer function can be written as: $y(t) = x_1(t)$, $\forall t \in \mathcal{T}(x_2)$, $y(t) = 0$ otherwise, $\mathcal{T}(x_2)$ being a variable subset, depending on the control input signal x_2, of the real time t for which the input signal should be passed to the output. Variable time discriminators often use clocked *transmission gates* and can be found in analog *multiplexers*, *sample-and-hold circuits* and *analog-to-digital converters*.

22. **Variable discrimination in frequency.** A variable frequency discriminator, or *controlled filter*, reproduces the input signal at its output only at certain variable frequencies or frequency bands. Its transfer function can be written as: $y(\omega) = x_1(t)$, $\forall \omega \in \Omega(x_2)$, $y(t) = 0$ otherwise, $\Omega(x_2)$ being a variable subset, depending on the control input signal x_2, of the real angular frequency ω for which the input signal should be passed to the output. Controlled filters, like ordinary filters, are often found in communication and audio systems.

23. **Variable discrimination in magnitude.** Finally, a variable magnitude discriminator delivers some function of the input signals at its output only for a certain combination of input signal levels. Its transfer function can be written as: $y = f(x_1, x_2)$, $\forall x_1 \in \mathcal{X}(x_2)$, $y = 0$ otherwise, $\mathcal{X}(x_2)$ being a variable subset, depending on the control input signal x_2, of the signal domain $\mathcal{D}$ for which the input signal should be passed to the output. Magnitude discriminators can be identified in, e.g., *comparators*.

V. CONCLUSIONS

In the foregoing sections, a new classification of electronic signal-processing functions has been presented, following a systematic approach. Via the identification of 5 classes, 3 subclasses and 3 signal domains, 23 elementary electronic signal-processing functions were found. Well-known examples of elementary electronic building blocks are classified. New elementary building blocks are defined, among which the "phaser," the "spreader" and some that do not have a name as yet.

It is believed that this classification of elementary electronic signal-processing functions will contribute to the understanding of their role in electronic circuits and will pave the way to new system architectures and eventually new electronic circuits. The classification can be used as an introduction to every freshman course on electronics and, in fact, is successfully used as such already by the Author at the Delft University of Technology for several years.

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