An Ear for Pythagorean Harmonics: Brain Models Built From Timing Devices

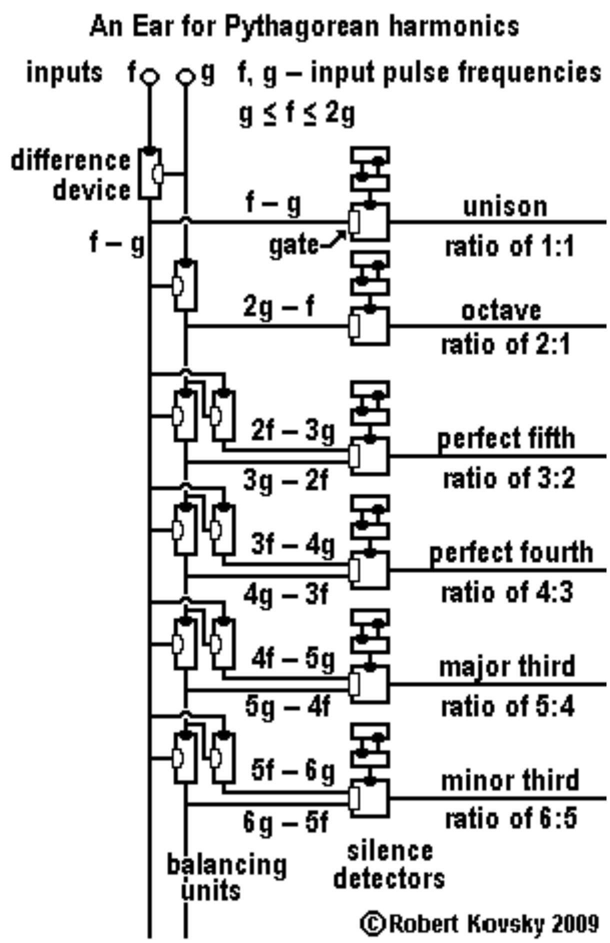
Abstract

"Timing devices" are proposed electronic inventions to be used in operating models of brains. Timing device designs, e.g., "an Ear for Pythagorean harmonics," resemble schematic diagrams for standard electronic circuits – but the principles are new and different. A "primal timing device" is defined and developed into a kit of complex timing devices. Proposed assemblies of timing devices detect stimuli, control muscle-like action and perform mathematical operations.

Signals in timing device assemblies are made up of "pulses," each lasting for only an instant. Device specifications and operational variables are stated in terms of "timing intervals." Pulse patterns and timing intervals control and change each other. Some patterns change abruptly and others go through gradual changes. Pulses and the timing of pulses make up all the phenomena.

A pulse is an idealization of an "action potential" that operates in nerves. Assemblies of neuron-like timing devices generate, organize and direct pulses. Timing device projects are stages in development of "engineered organisms" that perform activities similar to behaviors of animals, especially quick switching between behaviors, e.g., like a flock of birds that is startled into flight.

In an Ear for Pythagorean harmonics, "difference devices" perform frequency subtractions on pulse streams. Repeated subtractions generate an array of internal signals from a pair of input signals. "Balancing units" can produce a net null signal – silence – that opens a "gate" and denotes a specific ratio of input frequencies.



Simple ratios identify "Pythagorean harmonics." For example, if the two input tones are 660 Hz (pulses per second) and 440 Hz, the Ear detects and signals the presence of a "perfect fifth" based on the ratio of 3/2; and the same result occurs if the two input tones are 900 Hz and 600 Hz. If, however, the two input tones are 880 Hz and 660 Hz, the Ear detects and signals the presence of a "perfect fourth" based on the ratio of 4/3.

Operational features of the Ear parallel aspects of human auditory experience. Design features of the Ear suggest further ways to use timing devices to model behaviors of animals and the capacities of animals to select and switch behaviors.

Contents

A. Introduction: Timing Devices Are a New Way to Make Models of Brains.

"Timing devices" are a different approach to the question "how do brains work?"– an approach that is based on a new kind of electronic invention. Designs herein are entirely conceptual; I have no plans for working models. The main course of the presentation, beginning with point B, requires no factual knowledge; but it does require mathematical skills and imagination.

By way of introduction, timing devices have much in common with existing conceptual systems in science and technology; and timing devices also differ from such systems.

1. The timing devices system resembles the system of standard electronic circuits, where mathematical forms define idealized components (e.g., resistances, capacitances, transistors) and where an actual physical system built from a schematic diagram performs a specific function.

Activities in timing devices, like those in standard electronic circuit components, are defined in a mathematical way. Some timing device functions are similar to standard circuit component functions, e.g., "logical or," "logical and" and "gates." Timing device designs, similar to schematic diagrams for electronic circuits, call for connecting timing devices together into assemblies that perform specific functions. As in the early days of electronic circuit theory, specific goals and designs are points of origin for principled development.

2. Development of timing device systems aims to build "engineered organisms," where such an organism has a brain-like control system built from timing devices (and more general "Quad Net devices"), sensors that detect environmental influences and "twitching" muscle-like fibers that deliver impulses of physical force internally within the organism or to its environment. As controlled by signals from nerve-like timing devices, the engineered organism performs muscle-like "acts." It repeats acts and it also modifies acts and switches between acts according to "sensations," all in furtherance of a "purpose" or function. An engineered organism thus interacts with its environment through ***purposeful sensory-motor action***. Such action provides the substantial basis for a rudimentary artificial psychology constructed according to principles drawn from the psychology of Piaget. (Piaget, J., *Origins of Intelligence in Children*, etc.) A psychological unit called "following" is investigated herein (point E).

Action – repeated acts, modified acts, coordinated acts and switching between acts – constitutes the primal form of content in timing device systems. Action is controlled by internal clocks in timing devices; and clocks have individual and variable settings and rates. During operations, many different clocks in a timing device assembly are running independently. Timing devices go through changes "on their own," discharging pulses that can trigger changes in other timing devices, depending on momentary conditions. Such action is not within the reach of static forms used in conventional approaches to brain theory, such as finite-state-machine computerized models with representations that persist unchanged until altered by external command.

3. An engineered organism would be an idealized model of an animal organism. A large-scale system of timing devices, designed to control an engineered organism, would be an idealized model of a brain. The idealized timing device system resembles idealized physics models such as: the Ideal Gas Law, $pV=nRT$; Carnot's idealized Heat Engine; and idealized

constitutive laws in electrodynamics, e.g., Ohm's Law, V=IR in electricity.

An idealized model is a mental construction that has a mathematical character. A successful idealized model formalizes a principle that is experimentally realized in material bodies, under certain circumstances, in an approximate way. (Kant, I, *Critique of Pure Reason*, B x-xiv (Kemp Smith).)

For example, every actual gas will behave approximately like an ideal gas if the pressure is low enough and the temperature is high enough. The approximation can be made closer to the ideal by decreasing the pressure and increasing the temperature. Similar approximate actualizations occur, each in its own way, in relation to Carnot's Heat Engine and Ohm's Law. I suggest that there are situations – specific tasks in an environment – in which operations of timing device systems and behaviors of animal organisms similarly converge.

In background concepts, the timing devices system rather resembles Carnot's Heat Engine. Heat engines, both idealized and real – e.g., steam engines, automobile engines – convert heat energy into mechanical work through cyclical variations in operating parameters. Through similar cyclical variations, timing devices convert a steady inflow of energy into "pulses" that drive muscle-like fibers. In modeling brains, the energy inflow is attributed to "blood sugar." This model accords with PET scans that show, through relative presence or absence of blood sugar, which parts of a brain are highly activated and which are not.

The timing devices system incorporates "phase changes." A phase change occurs, for example, when liquid water vaporizes at a certain temperature – T=100° C – as it is heated, or when steam condenses at the same certain temperature as it is cooled. A very small change in temperature causes a complete change of form: this feature of phase change is found in many natural phenomena. "Irreversible phase changes" can happen so rapidly that details cannot be followed; and new forms can arise during an irreversible phase change that are un-reachable otherwise. Such phenomena are beyond the grasp of theoretical physics; but metallurgists and materials scientists have obtained substantial practical knowledge about, e.g., phase changes, both reversible and irreversible, that occur during quenching of steel. Using such knowledge, new forms of steel have been invented, e.g., "bainite," named for E. C. Bain.

I suggest that phase changes are of central importance for models of brains. Animals with relatively simple brains – insects, fish and birds – perform complex kinds of behavior, often collectively in a swarm, a school or a flock. Two kinds of complex behavior are "feeding" and "flight." Factually, quick switching from feeding to flight is well-nigh universal among animals. I suggest that "quick switching" extends throughout all kinds of behaviors, from that taking place on the largest scale to the most finely detailed. A chief question is therefore presented: "how do brains switch quickly from one complex activity to another complex activity?" I suggest that timing device systems provide answers to that question. The answers draw upon principles of heat engines and phase changes. I suggest that such principles open ways to ask and answer additional questions about brains and behavior.

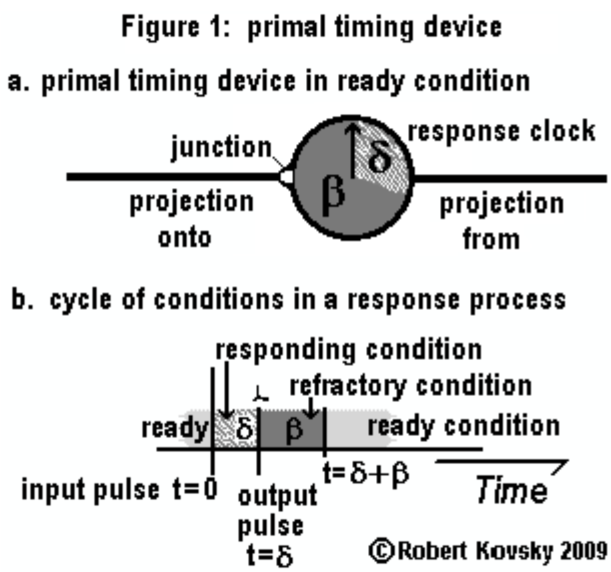
B. The Primal Timing Device.

1. Definition of the primal timing device.

The "primal timing device" models a very simple brain cell (neuron) and is the point of origin for development of more complex timing devices.

The chief part of the primal timing device is a "response clock" that is like a stopwatch used in sports contests, shown in Figure 1.a as a circular clock dial. Two "projections" connect the primal timing device to other timing devices. A "projection from" carries pulses away from the timing device. A "projection onto" carries pulses to the timing device. A "junction" connects the projection onto to the response clock. A pulse through the junction starts the "response process," which runs through a cycle of "conditions," during which it discharges a "pulse."

A pulse is a unit of signal, a packet of action. All pulses have the same shape and size. As a mathematical ideal, a pulse occurs instantaneously and resembles a Dirac delta function. Pulses travel on projections with infinite speed. These idealizations clarify the timing devices system. The more general Quad Net system uses pulses with various sizes and shapes. Methods for dealing with substantial travel times for pulses include re-definition of quantities, e.g., δ; symmetrical balancing designs; and compensating delays that are adjustable during operations.



As shown in Fig. 1.b, a primal timing device has a "ready condition," a "responding condition" and a "refractory condition." The device responds to an incident input pulse only when it is in the ready condition. In Fig. 1.b, an input pulse reaches a ready device at time $t = 0$, initiating the response process. The response clock starts and the device enters into the responding condition. At $t = \delta$, the device discharges an output pulse on the projection from; and the device enters into the refractory condition, which continues until $t = \delta + \beta$, when the device enters into the ready condition, completing the response process. δ is "the response period" and β is "the refractory period."

δ and β are the primal members of the class of "timing intervals," quantities that are set or varied as part of system operations. For precision of definition, the rule is that δ and β become fixed at the instant an input pulse reaches the device and remain fixed until the response process has run its course. Any adjustment of β or δ takes effect only when the device is in the ready condition.

Activity in timing device systems is described by instantaneous pulses. Activity in timing devices is specified by timing intervals. Pulsational instants of time and timing intervals make up the contents of timing device signals and operations. Initially, at least, there is nothing else.

2. Cycles: simple assemblies of primal timing devices.

Figure 2: 4-cycle and pulse train

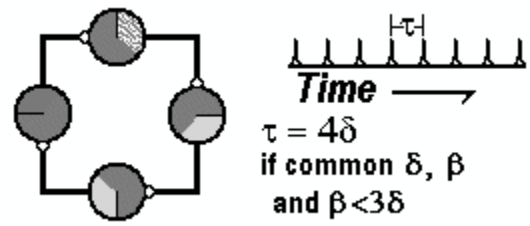


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Figure 2 shows four primal timing devices assembled into a "4-cycle." It is representative of a class of assemblies called n-cycles or, simply, "cycles." When a 4-cycle is running, each projection carries the signal denoted in the "Time" chart, namely, a sequence of pulses.

Timing devices in a cycle stand in relationship of "leader" and "follower" with one another. Each device is leader of one device and follower of another device. In an operating cycle, start at the moment a particular device triggers its follower device. The particular device then enters into the refractory period and later returns to the ready condition before its leader discharges.

The general form of a timing device signal is a "sequence of pulses." If pulses in a sequence are separated by a specific fixed period of time, τ, as in Figure 2, the signal is called a "pulse train." A pulse train is an ideal signal, described fully by its period. Other pulse sequences are irregular and cannot be described except by listing all the periods that succeed one another.

In Figure 2, the 4-cycle generates a pulse train with a period τ between pulses that is of size 4δ. Operation of the 4-cycle is possible only if $\beta<3\delta$. If $\beta>3\delta$, a timing device will not have become ready when its leader discharges. Suppose that a 4-cycle is producing a pulse train while $\beta<3\delta$ and that β is then increased until the pulsations cease. This is a rudimentary example of a kind of control that becomes increasingly ramified and refined as development proceeds.

The passage from $\beta<3\delta$ to $\beta>3\delta$ identifies a ***phase change*** at the point $\beta=3\delta$. It is like the phase change where liquid water changes into solid ice when the temperature is lowered. The change in water is described by stating that, as the researcher smoothly varies the temperature or T, the condition of the system changes abruptly, with the change occurring when T is exactly equal to 0°C. Abrupt phase changes are frequently encountered in simple materials, where they are called melting, vaporizing and condensing. The phase change concept applies to many kinds of phenomena, e.g., involving alloys, magnetism and liquid crystals.

In the timing device system, time and timing intervals take the place of temperature as the variable that controls a phase change. During a small passage of time, a timing device discharges a pulse or a pulse triggers activity in a timing device, resulting in a phase change. Such phase changes occur as the chief events in timing device systems not only on the smallest but on all larger scales. E.g., activity in one line will abruptly cease or activity in another line will abruptly commence as a timing interval – e.g., a pulse frequency – is changed by a very small amount. A timing device system implies a structure of phase changes, both abrupt and smooth, that are controlled by timing intervals. Such a structure is comparable to "phase diagrams" that map properties of metals and alloys as they change with temperature and other variables, such as the proportions of ingredients in an alloy.

3. Pulse wave in a string of primal timing devices.

Using a simplified style of imagery, Figure 3 shows a pulse wave passing through a string of primal timing devices. Time measurements are stated by reference to a “laboratory clock.”

Figure 3.a shows six primal timing devices joined to make up a string. The timing devices have a common response period δ and a common refractory period β, where β=2δ. The only input to the assembly is directed onto timing device a. The only output is the projection from timing device f.

In Figure 3.a, all six timing devices are in the ready condition. Each can be triggered; but an input from outside is needed to initiate activity. The assembly is “ready and waiting.”

Action starts in Figure 3.b with an input pulse onto timing device a at time t=0. Fig. 3.b.i shows conditions from just after t=0 until just before t=δ, a period of time denoted by (0, δ).

As time passes from t<δ to t>δ, timing device a discharges an output pulse and changes to the refractory condition. The output pulse from timing device a becomes an input pulse onto timing device b that triggers that device, starting its response clock and changing its condition to "responding."

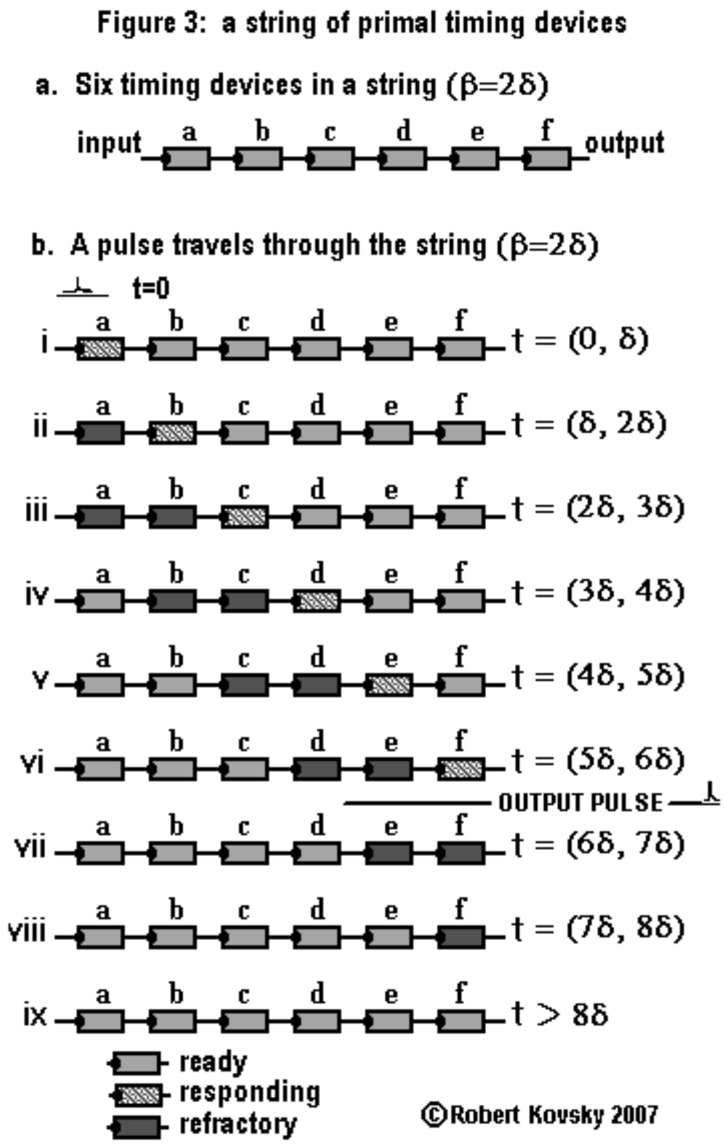


Figure 3.b.ii. shows the conditions between δ and 2δ. As time passes from t<2δ to t>2δ, timing device b discharges a pulse and changes to the refractory condition. The pulse discharged by timing device b triggers the response process in timing device c and starts its response clock, establishing conditions shown in Figure 3.b.iii. Timing device a remains in the refractory condition until t=3δ (=δ+β), when it again becomes ready.

As time evolves to and beyond t=3δ, each timing device successively reproduces the activity of its predecessor in the string; and the activity of each successive timing device is displaced in time by δ. In effect, δ is the "clock tick" that marks changes in conditions in the string. The pulse passes through the string and emerges as an output pulse at t=6δ, shown in Figure 3.b. After t=8δ, the string is again ready and waiting.

C. Complex Timing Devices

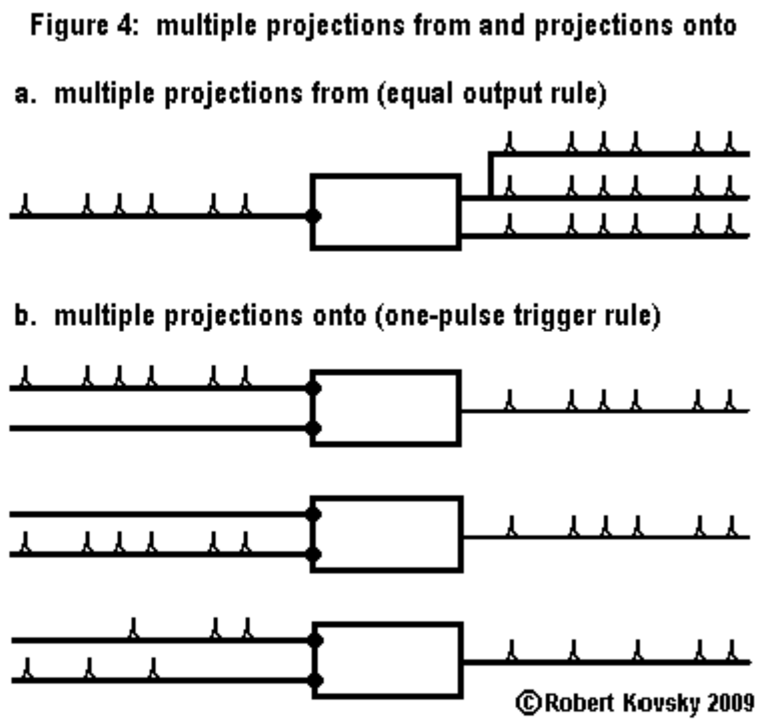
The primal timing device serves as the point of origin for development. A complex timing device acts like a primal timing device except for a specific change or addition that is to be described in full. Further complex timing devices are developed from the first complex timing devices in a similar fashion.

1. Timing devices that operate according to the "one pulse trigger" rule.

Figure 4 shows development of the primal timing device through multiplication of projections.

As shown in Figure 4.a, multiple "projections from" carry identical signals away from a timing device. This "equal output rule" governs all cases of multiple projections from. Projections from can ramify like tree branches and all branches carry the same signal.

Figure 4.b shows operation of multiple "projections onto" a timing device that is governed by the "one-pulse trigger rule." "One pulse" incident onto a ready timing device through ***any*** projection onto suffices to trigger the response process and start the response clock. The one-pulse rule resembles the "logical or."



Timing devices with multiple projections onto maintain the operating principle that an input pulse has no effect on device operations unless the device is ready. After the response clock has started and until the timing device returns to a ready condition, the timing device is unresponsive to input pulses arriving through any projection onto.

a. Pulse train generators; coupled timing devices.

The pulse train generator shown in Figure 5.a combines the string of Fig. 3 with the 4-cycle of Fig. 2. The shape of the 4-cycle is deformed. Such deformations are permissible in this simple timing devices system, as in standard circuit theory, where the speed of electricity is "infinite."

Compared to the string of primal timing devices in Figure 3, the pulse train generator has a new, additional projection that runs from timing device e onto timing device b. The assembly follows the equal-output rule and one-pulse trigger rule discussed previously.

Figure 5: pulse train generator

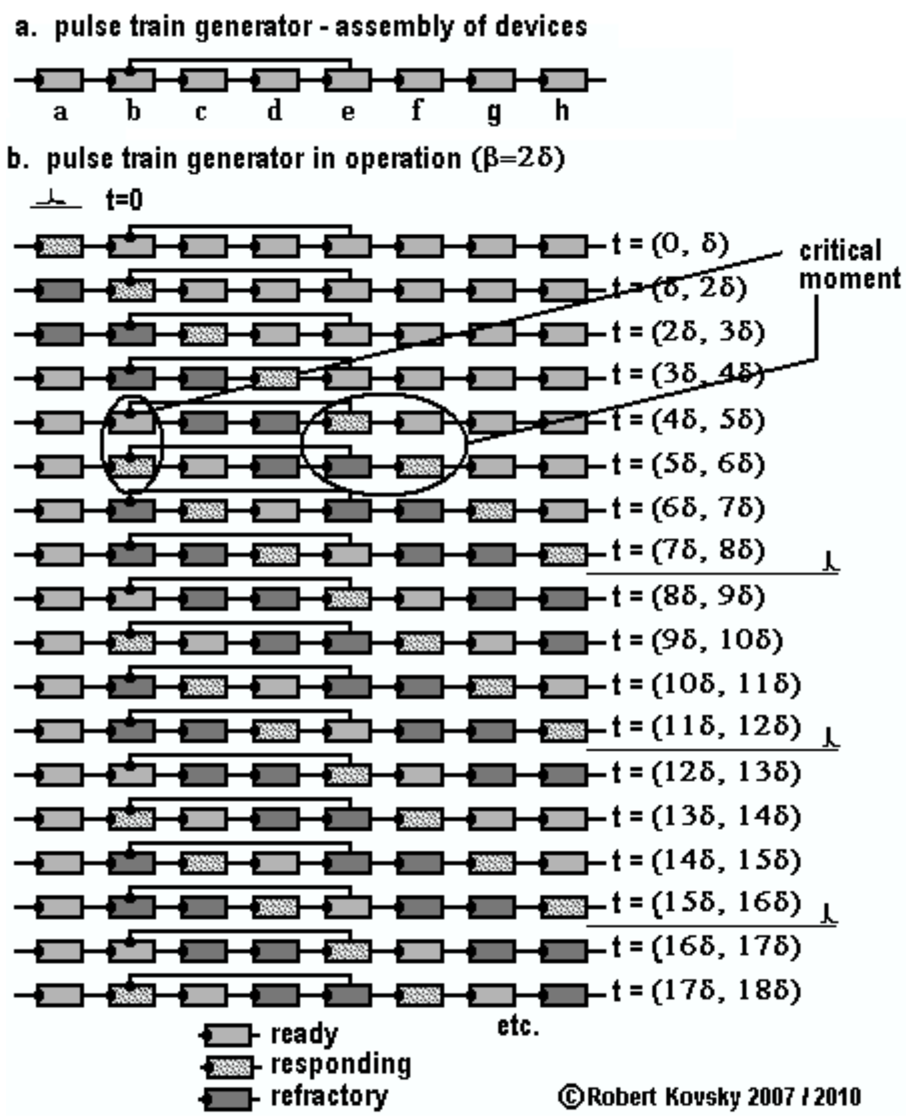
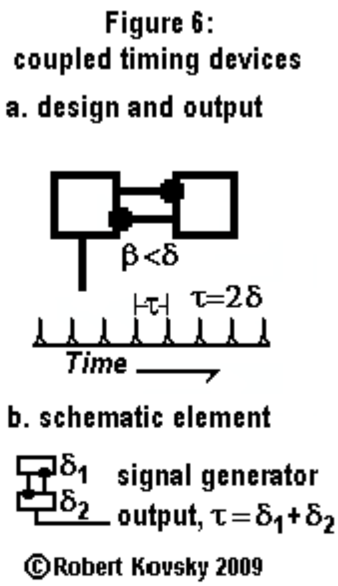


Figure 5.b shows what happens after a single pulse triggers the pulse train generator. For the first several clock ticks, the activity in Figure 5.b is like that shown in Figure 2. The "critical moment" in Figure 4.b occurs at t=5δ when timing device e discharges two pulses; one pulse

triggers timing device b through the new projection and one pulse triggers timing device f. The pulse discharged onto timing device b becomes circulating activity in the 4-cycle. The overall change from the simple string shown in Figure 3 is that activity continues "forever" instead of coming to an end after one pulse. That is, with a single input pulse at t=0, after a delay of 8δ, the assembly produces a repeating sequence of pulses, a pulse train, as output, with a period of 4δ between any two pulses in the sequence.



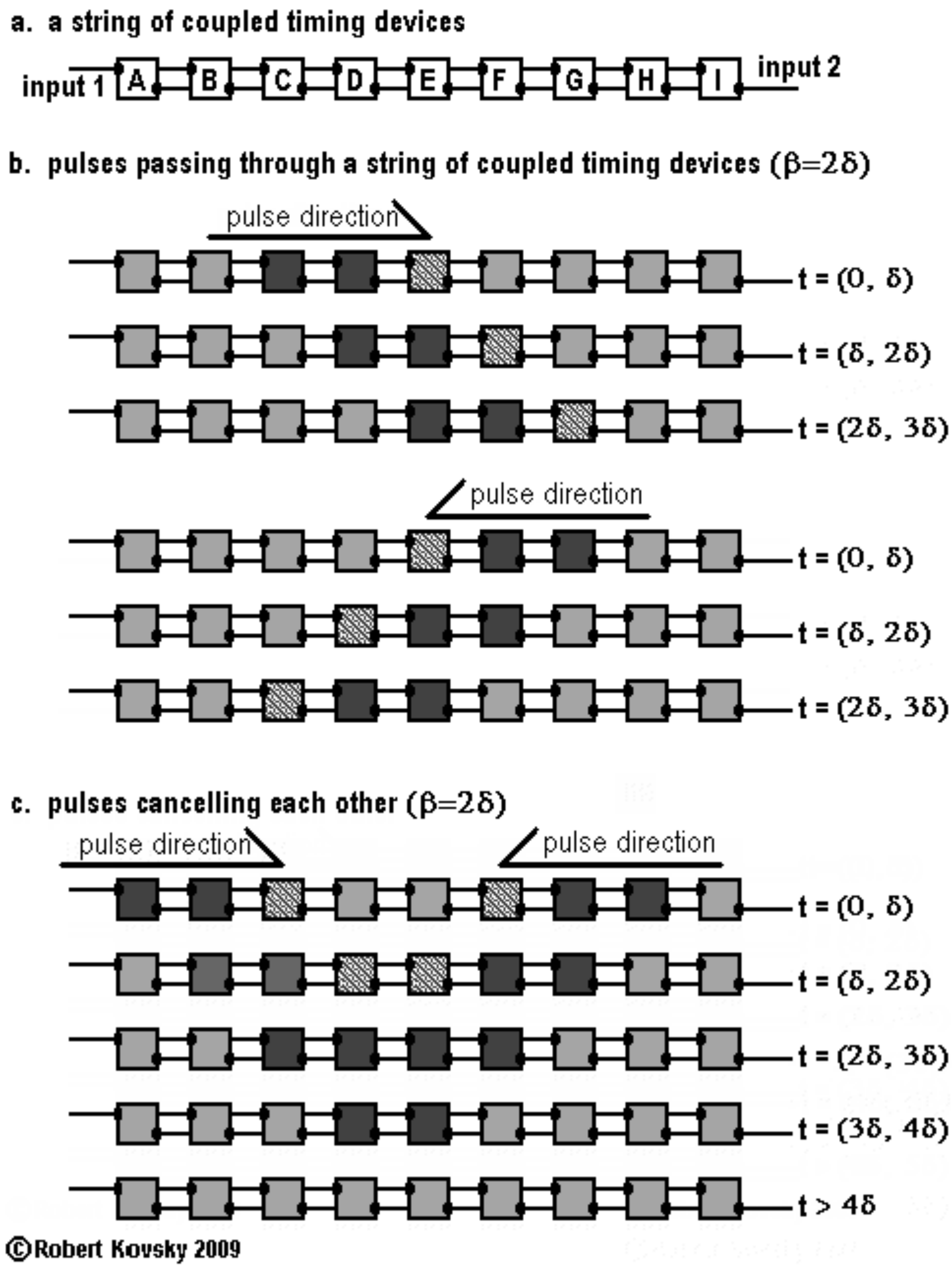
The “coupled timing devices” shown in Figure 6.a make up the smallest pulse train generator. The design is a “2-cycle” with an output projection from one of the timing devices. In Figure 6.a, the two timing devices are identical. Figure 6.b shows a simplified element of a “signal generator” for schematic designs with potentially different constituent timing devices.

The design in Fig. 6.a produces an output pulse train with $\tau = 2\delta$, while $\beta < \delta$. In more detail: when one coupled timing device discharges, it will trigger the response process in the other coupled timing device. Because β and δ are the same in both timing devices, the discharging timing device will return to the ready condition before the other timing device discharges and its response process will again be triggered. More generally, for the design in Fig. 6.b, the output pulse train will continue so long as both $\beta_1<\delta_2$ and $\beta_2<\delta_1$.

b. Pulse waves in a string of coupled timing devices.

Figure 7.a shows a string of "coupled timing devices." Each device is connected to each of its nearest neighbors by both a projection from and a projection onto. The "one-pulse rule" governs all timing devices. As shown in Figure 7.b, pulses can pass through such a string in either direction. If a pulse traveling in one direction meets a pulse traveling in the other direction, they "cancel" each other, as shown in Figure 7.c.

Figure 7: pulses in a string of coupled timing devices



Cancellation occurs in every case when pulses are directed against each other, including those where changes in timing device conditions are not synchronized (as they are in Figure 7.c).

An operational requirement for support of a pulse wave in a string of coupled timing devices is that β must be greater than δ. β need be greater than δ by only a tiny amount for support of a pulse wave. If, however, β is less than δ, even if by only a tiny amount, proper operations are impossible: the string discharges in a fixed way that cannot support a pulse wave.

Contrast the activity of the string of coupled timing devices where the constraint is $\beta > \delta$ with the activity of the coupled timing devices acting as a pulse train generator in Figure 6 where the constraint is $\beta < \delta$. In systems with coupled timing devices, $\beta = \delta$ identifies an important phase transition. A system will behave quite differently on the two sides of that transition.

For further analysis, recall that a pulse train is a sequence of pulses with a fixed period between any two pulses. To support a pulse train in a string of coupled timing devices, the cycle of activity must include a readiness period, γ, greater than 0; but $\gamma > 0$ need be no more than a tiny amount. This is symbolized $\gamma_{MIN} = 0^{+}$. Using similar symbolic forms for other timing intervals, the smallest cycle period, $\tau_{MIN} = \delta + \beta_{MIN} + \gamma_{MIN} = 2\delta$ + a tiny amount more, which is symbolized as $\tau_{MIN} = 2\delta^{+}$. The "+" here includes both $\beta_{MIN} = \delta^{+}$ and $\gamma_{MIN} = 0^{+}$.

Applying the result: If $\delta = 10^{-3}$ sec., the maximum workable frequency for the string is a bit under 500 Hz; if $\delta = 10^{-4}$ sec., the maximum workable frequency is just below 5000 Hz.

Attempts to operate the string at frequencies close to but above the cutoff will result in output pulse trains with exactly half the frequency of the input. In other words, operating just below the lower limit of the range of τ for perfect transmission, the string becomes a "frequency divider," passing every second ("even") pulse and failing to pass any intervening ("odd") pulses.

A similar analysis applies to a string of primal timing devices, Figure 3, supra. With primal timing devices, $\tau_{MIN} = (\delta + \beta_{MIN} + \gamma_{MIN})^{+}$ but there is no need for β_{MIN} to be greater than δ, as was the case for coupled timing devices, and the minimal β is 0^{+}. Hence $\tau_{MIN} = \delta^{+}$.

2. Timing devices that operate according to the "two-pulse trigger rule."

Figure 8 shows a complex timing device that is governed by the "two-pulse trigger rule." The rule is that two input pulses are required to trigger the response process and start the response clock; and both pulses must arrive at the timing device within a timing interval, ξ. ξ is an additional specification of the device. It doesn't matter which pulse arrives first. The two-pulse trigger rule resembles the logical "and."

Suppose, as shown in Figure 8.a, one pulse arrives at $t=t_a$ and another pulse arrives at $t=t_b$. If the absolute value of the difference in time of arrivals is less than ξ, i.e., if $| t_b - t_a | < \xi$, then the response process will be triggered. On the other hand, if $| t_b - t_a | > \xi$, there will be no response.

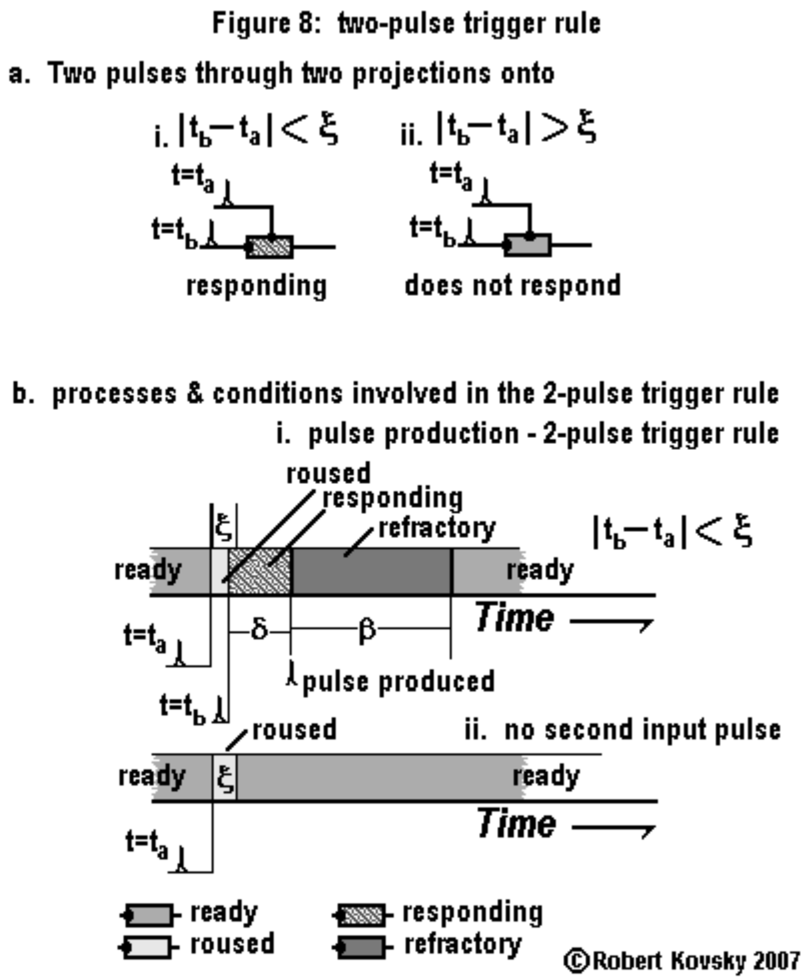


Fig. 8.b shows the processes and conditions involved in the two-pulse trigger rule in greater detail.

A new "device condition" is added to the device, the "roused condition." If the timing device is in the ready condition and a pulse arrives, the condition changes to the roused condition. If, while the timing device is in the roused condition, a second pulse arrives, the response clock starts and the condition changes to the responding condition. (See Fig. 8.b.i.)

If the roused condition continues for the full period of ξ without the arrival of a second pulse, the roused condition terminates and the timing device returns to the ready condition. (See Fig. 8.b.ii.)

In a timing device governed by the two-pulse trigger rule, there is an additional clock, the "rousal clock," that runs while the timing device is in the roused condition. The rousal clock is initially stopped (like the response clock). If a pulse arrives when the timing device is in the ready condition, the rousal clock is started. Unless a second pulse arrives while the rousal clock is running, the rousal clock terminates after the period of time denoted by ξ, the "rousal period," and the timing device returns to the ready condition. If a second pulse arrives while the rousal clock is running, that arrival triggers the response process and starts the response clock.

a. Frequency detector.

Figure 9 shows a frequency detector that acts like a bandpass filter in standard circuit theory. The design is shown in Fig. 9.a, where timing device g is governed by the two-pulse trigger rule and has an additional projection onto. All other timing devices remain governed by the one-pulse trigger rule.

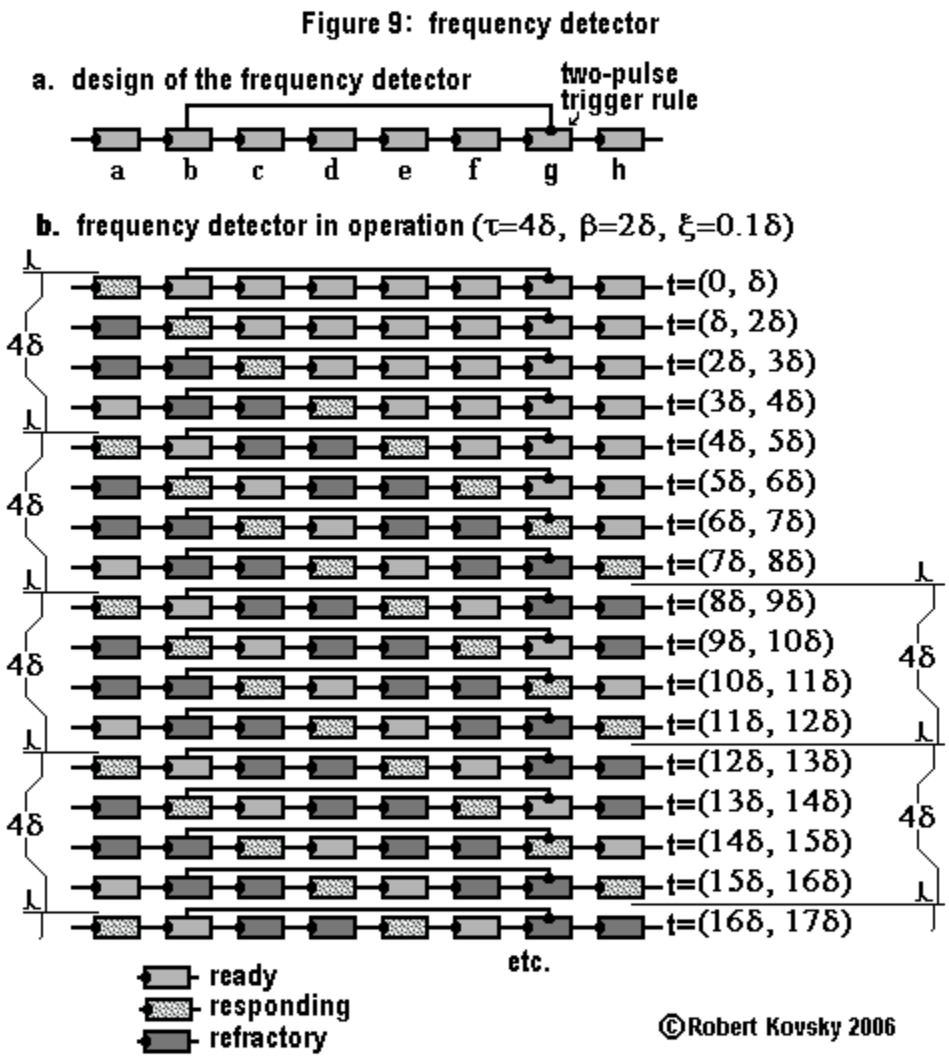


Fig. 9.b shows the frequency detector in operation while detecting a pulse-rate of τ=4δ. The pulses in the Figure arrive at both junctions of timing device g at exactly the same instant, triggering the response. If τ=5δ or τ=3.5δ, arrivals at timing device g are distinct and there will be no output. Examination shows that the frequency detector will pass pulses that arrive in a pulse train of period τ if $(4\delta - \xi) < \tau < (4\delta + \xi)$; or, for the specification of Figure 19.b, for a period $3.9\delta < \tau < 4.1\delta$.

{Note. Fig. 19.b omits a line showing g as "roused" for the time period t=(δ, δ+ξ).}

b. Frequency analyzer.

Figure 10 shows the general design for a "frequency analyzer," where a pulse train appears on exactly one line depending on the period of the pulses.

The coupled timing devices at the top act as a signal generator (Fig. 6.b). The response period of one coupled timing device is fixed (δ_A) while that of the other is an independent variable (δ). The signal on the projection from the signal generator is a pulse train with a period $\tau = (\delta_A + \delta)$.

Design goals are as follows: If the signal generator is producing a pulse train with a δ that is within a certain range of values, the signal appears on exactly one output line. As δ is increased from a minimum value, the signal appears first on line 0, then on line 1, and so forth, in a regular way such that each line carries signals for a defined frequency band. The frequency bands make up and partition the frequency spectrum within the range of δ.

Figure 10: frequency analyzer (general)

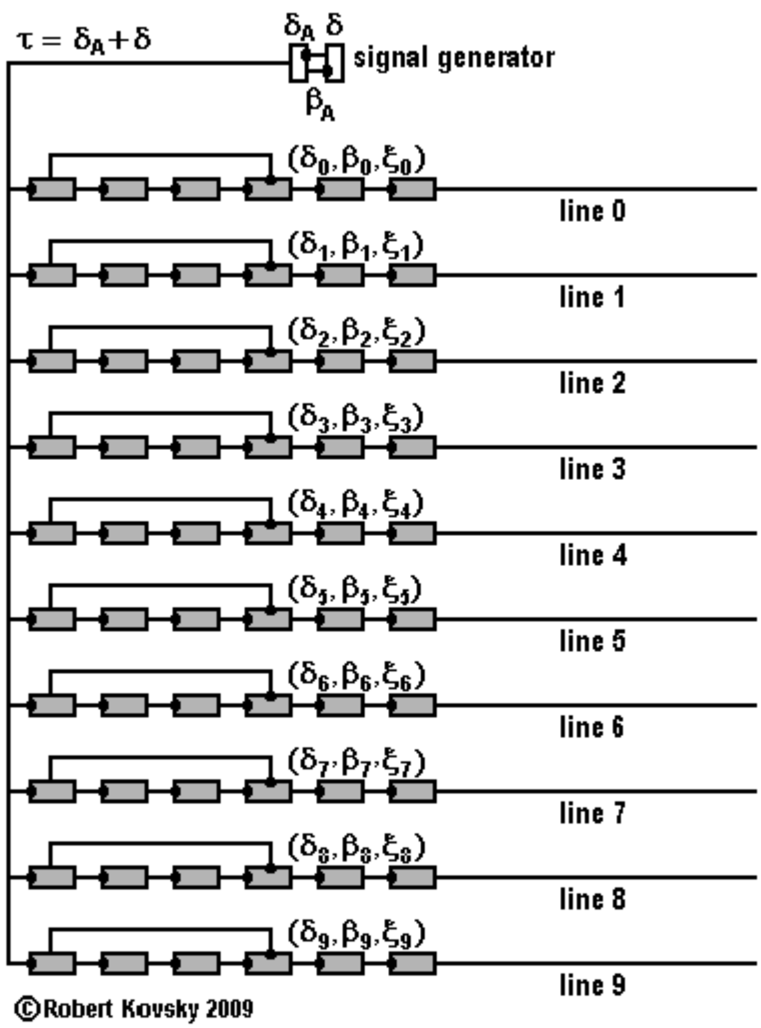
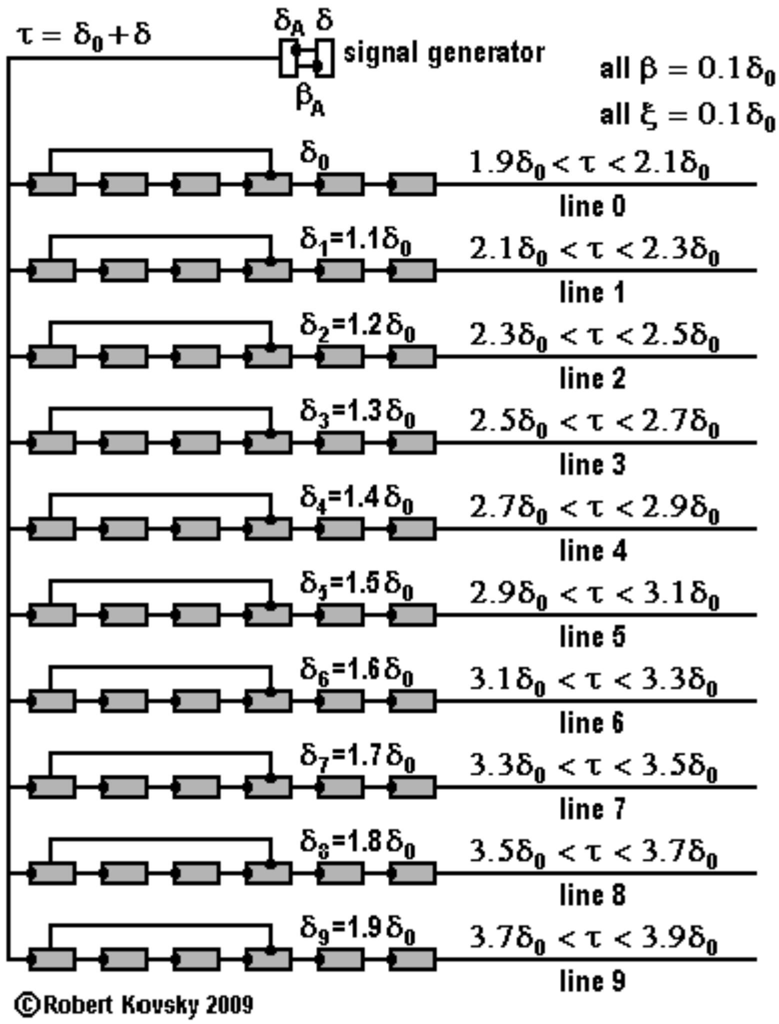


Figure 11 shows the system outlined in Figure 10, but with suitable settings for specifications. Specification δ_0 sets the time standard or reference. The variable in the signal generator – δ – can range from $0.9\delta_0$ to $2.9\delta_0$; and τ can correspondingly range from $1.9\delta_0$ to $3.9\delta_0$, spanning more than a full octave. The β_j for all timing devices are equal to $0.1\delta_0$. The ξ_j in timing devices governed by the two-pulse trigger rule are equal to $0.1\delta_0$.

Figure 11: frequency analyzer (specified)



Suppose δ starts at less than $0.9\delta_0$ (τ less than $1.9\delta_0$). All lines will be silent. Then, suppose δ is increased. As δ reaches $0.9\delta_0$, the signal appears on line 0. The signal stays on line 0 while δ increases until, abruptly at $\delta = 1.1\delta_0$, the signal disappears from line 0 and a signal appears on line 1. As δ increases continuously, the signal disappears and appears on successive lines in a step-like fashion. Activity on each line constitutes a separate phase. Passage through the structure of phases is controlled through variation in δ.

3. Timing devices based on secondary "modulation junctions."

a. Gate modulations: the silence detector.

Figure 12 shows a "gate timing device." It has functional parallels to conventional electrical and electronic circuit components that have the nature of "gates" or "valves" – e.g., electrical relays, vacuum tube triodes and "npn" transistors – but with new kinds of signals and operations.

As shown in Fig. 12.a, a gate timing device has two different junctions. The "input" projection onto and the "trigger junction" have the same function and operations as in the primal timing device. In addition, a second projection onto the timing device, called the "line" in Figure 12, attaches through a different kind of junction, called a "modulation junction." "Modulation pulses" are carried through the line onto the modulation junction.

Figure 12: gate timing device

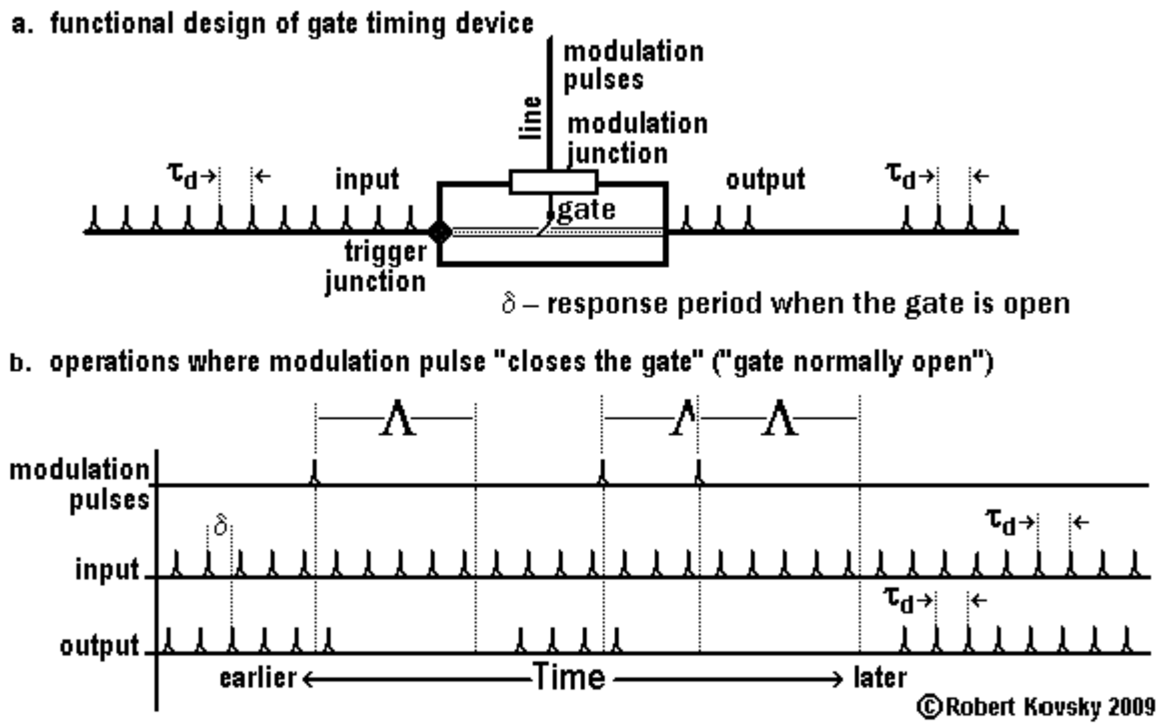
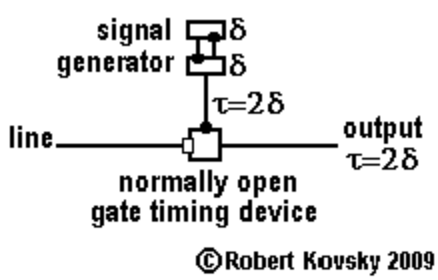


Figure 12.b shows the operations of the "gate normally open" gate timing device. An input pulse leads to a primal, delayed output pulse when "the gate is open" but the output is silent when "the gate is closed." A modulation pulse closes the gate for a period of Λ, the "modulation period." The gate is closed as to input pulses arriving after the arrival of the modulation pulse; there is no interruption of a response process initiated prior to the arrival of the modulation pulse.

If a modulation pulse arrives while the gate is closed, the gate will remain closed for Λ additional seconds, or longer, if more modulation pulses arrive. If modulation pulses arrive at a frequency greater than 1/Λ, the gate will be maintained in a closed condition.

Figure 13.a shows a design for a "silence detector," using the signal generator shown in Figure 6.b and the "gate normally open" timing device" shown in Figure 12.b.

Figure 13: silence detector

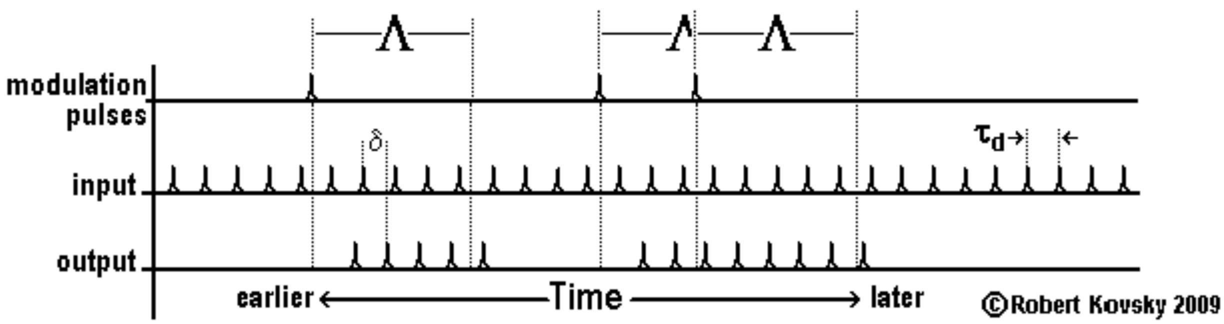


The gate in the silence detector, normally open, stays open so long as "the line is silent," meaning that there is no signal on the line. While the gate is open, the output is a pulse train produced by the pulse train generator.

In operation, the silence detector shuts off output when pulses on the line arrive faster than once every Λ seconds. Conversely, if an otherwise-active line falls into silence, the silence detector will signal that fact with an output pulse train. It is the latter capacity that is used in the Ear for Pythagorean harmonics.

There is also a "gate normally closed" timing device where the gate is closed when the line and modulation junction are silent and where a modulation pulse opens the gate for a period Λ. The activity of the gate normally closed timing device is shown in Figure 14. Compare to Figure 12.

Figure 14: a modulation pulse opens a gate that is normally closed



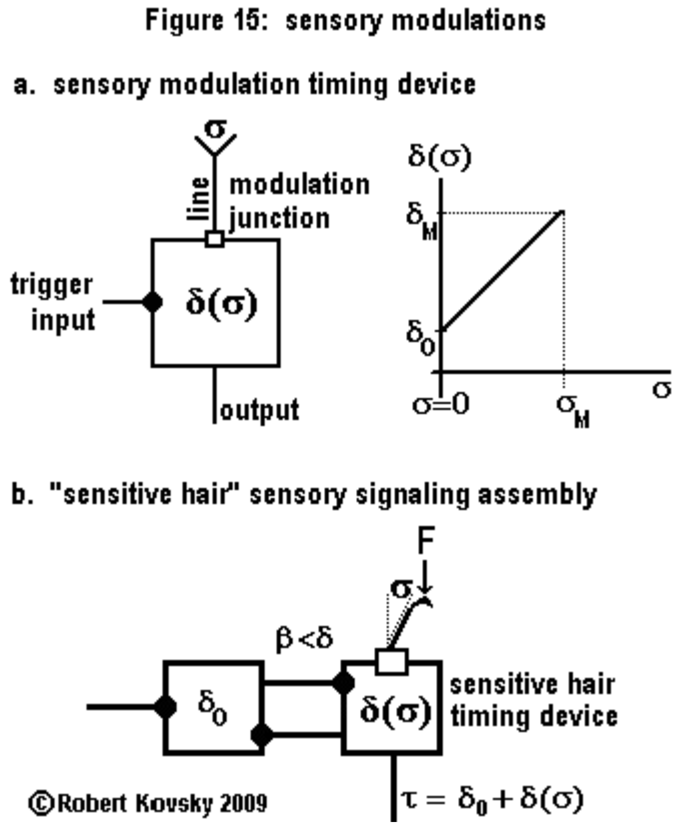
b. Graded modulation: sensitive hair.

Figure 15 shows the operation of "sensory modulations" in a "sensory modulation timing device."

A general sensory modulation timing device is shown in Figure 15.a, where the trigger input continues the primal function. A variable sensory stimulus – σ – modifies the responding period – δ. The chart in Figure 15.a shows a simple linear relationship between the strength of a stimulus and the length of the responding period.

The value of δ at the instant of trigger becomes the response period for that cycle. If there is no sensory input, $\sigma = 0$, and δ_0 is unmodulated. A modulation input results in a longer response period, δ, leading to a slower response process. The longest response period, δ_M, results from a maximum significant sensory input, σ_M.

Figure 15.b shows a "sensitive hair" sensory modulation timing device that is coupled with an ordinary timing device to make up a sensory signaling assembly.

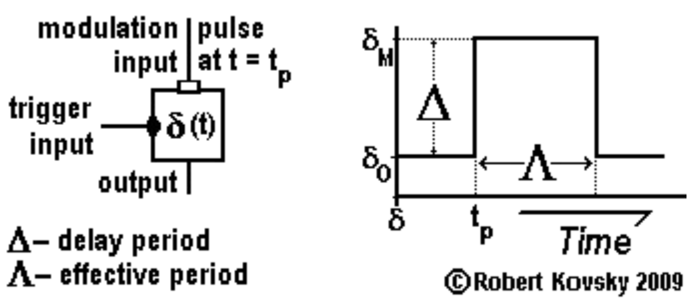


Conceptually, the sensitive hair is attached to the timing device through a mechanical fitting that responds to a force or pressure F by bending to an angle, σ. A simple elastic fitting would yield an angle that is proportional to the pressure, that is, $\sigma=kF$. Using such linear form, the output sensory signal has a period: $\tau = [\delta_0+\delta(\sigma)] = \delta_0(2+kF)$, providing a signal that detects and measures the stimulus F.

c. Delay modulations: summation device.

Figure 16 shows another complex timing device, called a pulsational delay device.

Figure 16: pulsational delay device

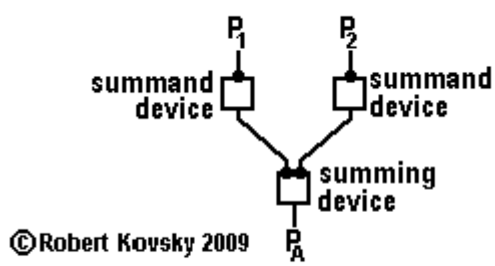


A pulse arriving at the modulation input of the device changes the responding period δ for an "effective period" of time, Λ. Normally, the response period is δ_0 but it is lengthened for the effective period. If a modulation pulse arrives at $t = t_p$, and another pulse arrives at the trigger input at any time between t_p and $(t_p + \Lambda)$, the response period will be $\delta_M = \delta_0 + \Delta$, adding a "delay period" Δ.

In the same way as with the gate timing device, if a second modulation pulse arrives at the pulsational delay device during the Λ period, the modified δ – i.e., δ_M – will be extended for a further period of Λ from the time of the second pulse.

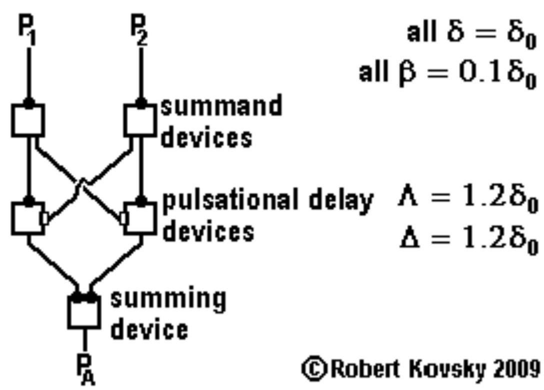
As shown in Figure 17, pulse summation cannot be carried out simply by inputting two signals through two projections onto a "summing device." Suppose there are two pulses through the two lines, first a "leading pulse" through one line and then, very shortly afterwards, a "lagging pulse" through the other line. The arrival of the leading pulse will trigger the summing device and make it unresponsive to the lagging pulse that arrives through the other projection onto shortly thereafter. This lapse causes in error in the sum.

Figure 17: combining pulse streams



The summation device shown in Figure 18 uses pulsational delay devices so that the passage of a leading pulse causes a ***delay*** in the arrival at the summing device of a "lagging" pulse; and the delay will last until: the leading pulse has cleared through the summing device; the summing device has passed through the refractory period; and the summing device has returned to the ready condition. A constraint, τ_{MIN}, is imposed on the period between input pulses to ensure that pulses arrive slowly enough that the device "clears out" between delay processes.

Figure 18: summation device



In Fig. 18, two pulse streams P_1 and P_2 flow in two branches. Suppose the system is clear when a pulse arrives through the P_1 projection and that another pulse arrives through the P_2 projection shortly after. The P_1 pulse activates the P_1 summand device, which then (1) triggers the pulsational delay device in the P_1 branch and (2) modulates and delays the response process in the pulsational delay device in the P_2 branch. If the aforementioned P_1 pulse arrives at the summing device at $t = t_p$, the P_2 pulse will arrive at that device shortly after $t = t_p + 1.2\delta_0$, following the delay of Δ=$1.2\delta_0$. The summing device will have returned to the ready condition at $t = t_p + 1.1\delta_0$.

The delays operate so that the frequencies of the pulse streams are, indeed, summed at the summing timing device. If the frequency of P_1 is "20 pulses per second" and the frequency of P_2 is "12 pulses per second," the frequency of P_A is "32 pulses per second."

Two features call for further discussion.

First, the minimum period, τ_{MIN}, for the pulse streams should be defined. This is equivalent to defining the maximum pulse frequency the device assembly can handle. If the pulse stream were passing through a string of primal timing devices, τ_{MIN} would equal $(\delta + \beta)^+$. In particular, τ_{MIN} would equal $1.1\delta_0$ for a primal timing devices that has timing intervals δ_0 and $\beta = 0.1\delta_0$, used in Figure 18. (See discussion at the end of point C.1.b.)

For the assembly of Figure 18, the result, shown through the following discussion and Figures, is as follows: $\tau_{MIN} = 3.5\delta_0^+$ for P_1 and P_2; $\tau_{MIN} = 1.75\delta_0^+$ for P_A.

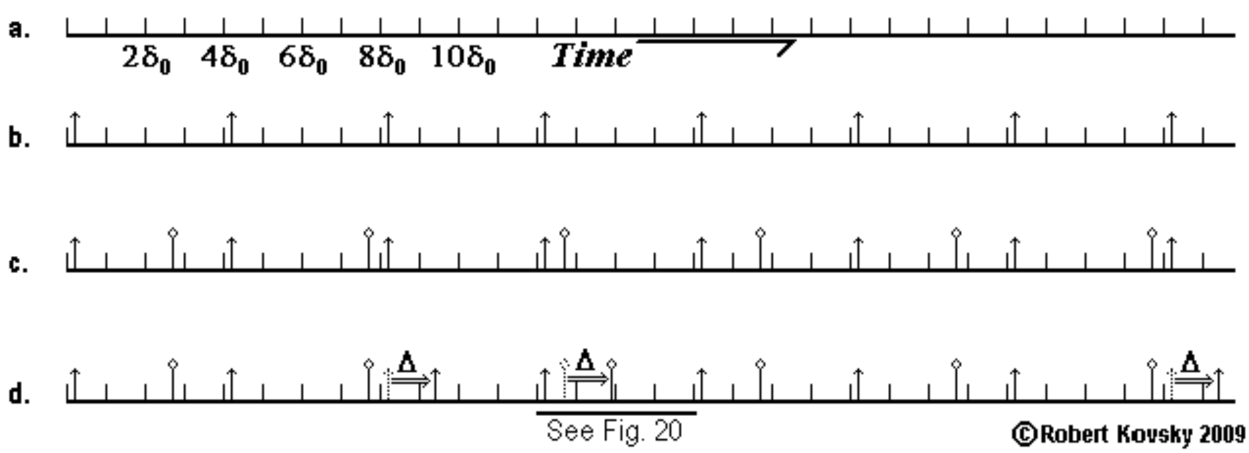
Second, the pulse stream P_A is irregular, with multiple values for τ, the period between pulses. The average is fixed but the average must be taken over a bloc of time. This feature identifies important questions about signals, discussed in point D.

Figure 19 shows pulse streams in the summation device. The time scale for pulse streams is shown in Figure 19.a, where δ_0 is the elemental unit of time. In other words, a spatial unit in Fig. 19.a denotes the time between stimulus and response in the timing device. Pulses are charted as events that occur at a certain time according to a reference or laboratory clock. For convenience, the reference clock is marked in units of δ_0 and is started at t=0.

Fig. 19.b. shows a pulse stream passing through P_1 where $\tau = 4\delta_0$.

Fig. 19.c shows the addition of the pulse stream passing through P_2 where $\tau = 5\delta_0$. The signals passing through P_1 and P_2 are superimposed on a single time scale; but with no delays or summing. Note that the pattern repeats every $20\delta_0$.

Figure 19: pulse streams in the summation device

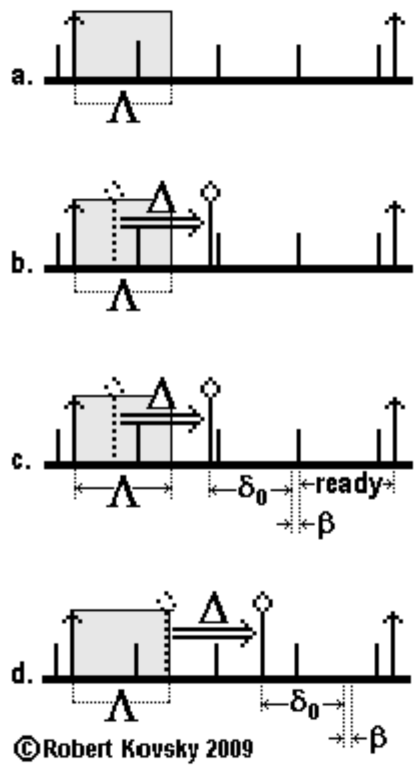


Pulsestreams are combined on arrival at the summing device according to the one-pulse trigger rule. If combined pulsestream shown in Fig. 19.c were to arrive at the summing device, some pulses would be “lost” because the summing device would not be ready for them. The delays shown in Fig. 19.d correct this error. When a pair of pulses would be arriving too closely together for both to be counted, the later pulse is delayed or shifted in time so that readiness of the summing device is assured. The shift is $1.2\delta_0$, more than enough. The shifted pattern repeats every $20\delta_0$ and averages taken over that time (or longer) tend toward $<\tau> = (20/9)\delta_0$.

Figure 20 examines timing intervals in the summation device, with an expanded view of the marked part of Fig. 19.d. Two pulses from P_1 define the period of interest in Figure 20.

Fig. 20.a shows the "effective period" of the modulation. A delay will be imposed on pulses in the P_2 branch, but only for a certain period of time, denoted by Λ.

Figure 20: timing intervals in the summation device



The effective period is different from the "delay period," denoted by Δ. As shown in Fig. 20.b, the pulse from P_2 is effectively delayed or shifted by a period of time Δ.

Suppose a pulse from P_1 reaches the summing device while it is in the ready condition. (Fig. 20.c.) The pulse from P_2 is delayed. Once that delayed pulse triggers the summing device, that device will pass through the responding condition (δ_0) and the refractory condition (β) before it (the summing device) returns to the ready condition.

The operating constraint τ_{MIN} is ascertained by noting that the most demanding signal (the signal requiring the most processing time) occurs when the pulse from P_2 arrives at the summand device Λ^{-} after the arrival of the pulse from P_1, that is, at the very last moment that the delay is effective. Activity for the most demanding signal is shown in Fig. 20.d. After the delay of Δ in the pulsational delay device, the summand device receives the P_2 pulse and cycles through the response process, requiring more time, $\delta_0 + \beta$.

For the activity in Fig. 20.d, the total time before the summing device returns to the ready condition, after having been triggered by the pulses from P_1 and P_2, is the sum: $\Lambda + \Delta + \delta_0 + \beta$. This is shown graphically in Fig. 20.d.

The summed period of time is the value of τ_{MIN}. That is, $\tau_{MIN} = \Lambda + \Delta + \delta_0 + \beta$. As long as P_1 pulses arrive with a τ greater than τ_{MIN}, the summing device returned to the ready condition before each pulse arrives. Such return will occur regardless of when the pulse from P_2 arrives, so long as it is the P_2 pulse that is being delayed. (If the P_2 pulse arrives shortly before the next pulse through P_1, that P_1 pulse will be the one delayed – but such a state of affairs is a variant of the original problem with indices exchanged and that problem is directly solved in the fashion shown in Figures 19 and 20.)

The most demanding signal for the summation device – based on the fragment shown in Fig. 19.d – is constituted by two equal pulse trains, P_1 and P_2 where each pulse train has a period τ_{MIN} (with a specific temporal displacement). For the specifications in the example, $\tau_{MIN} = 3.5\delta_0^{+}$. Thus, the pulse trains that are used for P_1 and P_2 in the Figures ($\tau = 4.0\delta$ and $\tau = 5.0\delta$) are within the constraint imposed by τ_{MIN}. To calculate τ_{MIN} for P_A, recall that the pulse stream through P_A carries as many pulses as the sum of the streams through P_1 and P_2. Therefore, the τ_{MIN} for P_A is

$1.75\delta_0^+$. This is well within the primal timing device τ_{MIN} of δ^+.

The summation device works for the most demanding signal, $\tau_{MIN,}$ and for all less demanding signals, i.e., where τ is greater than τ_{MIN}. On the other hand, loss of pulses will occur if signal constraints are violated, e.g., if $P_1 = P_2 = 3.0\delta_0$ with P_2 pulses lagging those in P_1 by $\Lambda^-_.$ Other less demanding signals may not lose pulses until τ becomes much smaller than τ_{MIN}. E.g., the signal that resembles the most demanding signal except that the lag is Λ^+. For such a signal, no pulse is delayed. Then, $\tau_{MIN} = \Lambda + \delta_0 + \beta = 2.3\delta_0$ for the specifications here, a τ_{MIN} substantially less than the τ_{MIN} for the most demanding signal, previously discussed.

D. Timing Device Signals

1. Signals in timing devices occur in several forms, including ideal pulse trains, ideal pulse bundles and irregular approximations of ideal signals.

The general form of signal in timing devices is the "pulse stream" or "pulse sequence." In the ideal system constructed here, each pulse has an instantaneous existence during which it travels between timing devices. All pulses are identical.

In general, the amount of time or "period" between two successive pulses – denoted by "τ" – varies without constraint so long as it is greater than τ_{MIN}. An ideal kind of pulse stream is the "pulse train," which has a fixed, uniform or regular period τ between any two pulses. Within the pulse train form, only the period can vary.

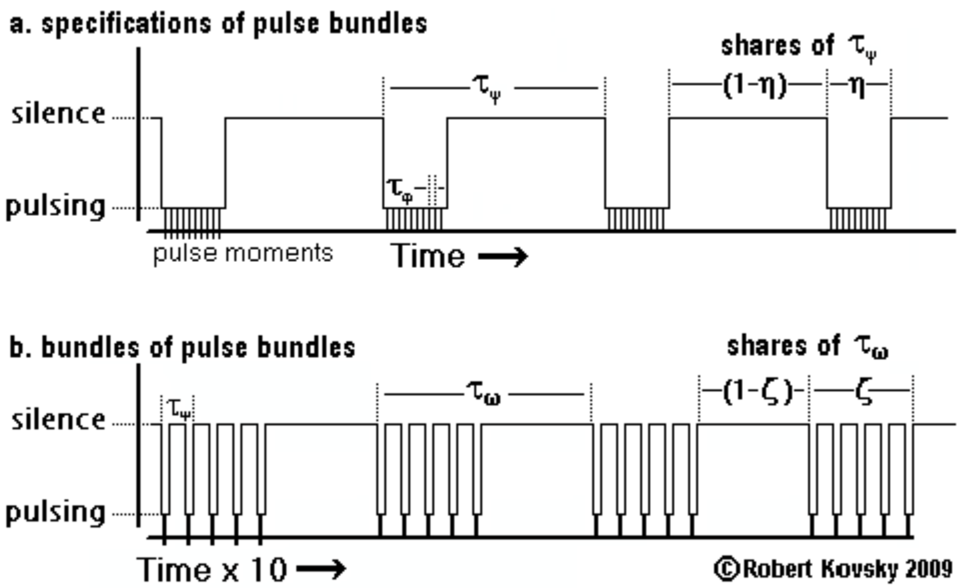
A pulse train is characterized by a "frequency." The frequency is the inverse of the pulse period, that is, $f = (1/\tau)$ where τ is fixed. A "random" pulse stream, where τ's are unrelated and vary over a wide range, has no frequency that can be defined. There are intermediate forms of signals that have manageable irregularities and I call such signals "sufficiently defined," . E.g., a highly regular but less than ideal pulse stream consists of "pulse train segments" with continuous transitions: during most of the time, namely, during the passage of the "pulse train segments," periods are exactly repeated many times; and when changes occur, between pulse train segments, the difference between any two successive periods is relatively small when compared to the period, so that any change occurs slowly.

The pulse stream that is produced by the summation device of Figure 18 – P_A – has an irregular flow of pulses. Such an irregular pulse stream can be used as an input stream into another summation device – as P_1 or P_2 – so long as each τ between pulses in the P_A stream coming out of the first device is greater than the τ_{MIN} that limits P_1 and P_2 input to the second device. With such constraints, clearly achievable, a cascaded network of summation devices should operate properly with irregular pulse streams.

In contrast, an irregular pulse stream produced by the summation device will not work in the frequency detector or the frequency analyzer, shown in Figures 9-11. Those devices require that the period between pulses be uniform to within a value of 2ξ, where $\xi=0.1\delta_0$. Irregularities in the pulse stream produced by the summation device are of the magnitude $\Lambda = 1.2\delta_0$, a far larger quantity. The frequency detector and frequency analyzer properly include the word "frequency" in their names because they will not operate with irregular signals.

A second idealized pulse stream is a stream of ideal "pulse bundles." In contrast to a pulse train – where the only specification is τ – pulse bundles have three specifications, τ_φ, τ_ψ and η, shown in Fig. 21.a. The cycle of the pulse bundle is organized by τ_ψ, the "organizational period." A fraction of that time period – $\eta \cdot \tau_\psi$ – is a period of pulsing and the remaining fraction – $(1 - \eta) \cdot \tau_\psi$ – is a period of silence. Within each ideal pulse bundle, τ_φ is the uniform period between pulses and is called the "signal period." The number of pulses in a bundle, n, is equal to the largest integer in $\eta \cdot (\tau_\psi / \tau_\varphi)$ – perhaps subtracting 1, depending on the exact timing of pulses.

Figure 21: pulse bundles



The greater number of variables in pulse bundles, compared to a pulse train, provides more ways to exercise control. For example, it is possible to hold both τ_ψ and n constant while η and τ_φ are varied together in a linear fashion. Such a linear variance is different from the inverse variance that occurs if τ_ψ is increased and η is decreased so that the bundle itself – and n and τ_φ – are held constant. One difference is that the average flow of pulses in the pulse stream is unchanged by a variance of the first kind but is changed by a variance of the second kind.

Pulse bundles allow for yet a further kind of organization. More advanced signals take the form of "bundles of pulse bundles" shown in Fig. 21.b. Additional specifications τ_ω and ζ provide for greater control. Such signals are suitable for complex assemblies where activities patterns make up "cycles within cycles." E.g., a musician plays a set of triplets between every two taps of her foot; a swimmer using a crawl stroke fits 6 flutter kicks into each arm cycle and fits two arm cycles into each breath cycle.

A device assembly that works with pulse trains may require modifications for operations with pulse bundles. E.g., the summation device can be used with pulse bundles so that the number of pulses in a bundle produced as output, n_A, is equal to the sum of the numbers of pulses in the bundles of the two input streams, n_1 and n_2. As an operating constraint, the two input bundles must share a common τ_ψ and must commence passage through the two inputs at close to the same instant; that is, the organizational cycles of the input pulse bundles must synchronized (synchronization is shown in Figure 43).

2. Pulse bundles are suited to drive twitches of muscle-like fibers.

Within a larger conceptual context, as stated in the Introduction, timing device systems are directed towards construction of engineered organisms, which engage in purposeful sensory-motor action. Point E.2 includes designs for engineered organisms that follow a light. Motor action is performed by muscle-like fibers that twitch. In a larger-scale engineered organism, twitchings sets of fibers would be organized to perform physical acts using the organism's equivalent of a musculo-skeletal system. The acts that the twitchings perform establish the foundational action patterns of the organism, its "repertoire of acts."

Pulse bundles provide a code for twitching that matches up with the activity of muscle-like fibers. A twitch is an impulse, defined as a force acting for a time, usually short. In the simplest code, the force of a twitch varies inversely with the period between pulses. Faster pulses produce more force, within a range of activity. The twitch lasts as long as the bundle of pulses.

For a pulse bundle with uniform pulsing period, τ_φ, the code states that the muscle-like fiber exerts a uniform force during the processing of the bundle. The force is proportional to $(1/\tau_\varphi)$.

Pulse bundles in timing device systems appear to resemble "bursts" of action potentials produced by neurons that control muscular movements in animals. A burst consists of a fast series of action potentials followed by a quiet period. For example, A. G. Millar & H. L. Atwood report on two kinds of motor neurons in lobsters and crayfish, a "phasic" kind that produces bursts of action potentials and that results in fast muscle twitches and a "tonic" kind that is slower and summational. (*Crustacean Phasic and Tonic Motor Neurons*, INTEGR. COMP. BIOL., 44:4–13 (2004), http://icb.oxfordjournals.org/cgi/content/full/44/1/4) Researchers of muscular activity in biological organisms, including human beings, confirm that, to a first approximation, the frequency of action potentials in a nerve signal codes for the force of the muscular contraction caused by the signal. (See Kandel, E. R., Schwartz, J. H., Jessell, T. M., 1991, *Principles of Neural Science*, Appleton & Lange, 3d ed. at 553-556, 614-615, 672).

3. A “streaming device” uses a ratio (n/m) to calculate output pulse periods from those of an input pulse stream, serving as a frequency multiplier.

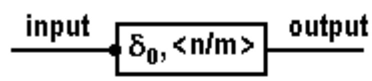
Some signals, e.g., pulse bundles, have a large-scale organization that extends over a considerable period of time and includes many pulses. An additional class of timing devices – called “convolution devices” – deals with such extended signals. The name comes from an operational resemblance to the “convolution integral” that is used in standard circuit theory to organize families of signals.

Figure 22 shows the schematic element for the “streaming device,” a simple example of a convolution device.

The streaming device inherits the response process, response clock and response period (δ_0) from the primal timing device. The refractory period β is small and insignificant.

The schematic element for the streaming device has specifications δ_0, n and m. Specification n is the “lookback number” and specification m is the “averaging factor.” n is an integer ≥ 1 and m is a real number > 0. The general conception of the device allows for variance in n and/or m during operations. δ_0 is a fixed and foundational quantity, at least initially.

Figure 22: specifications of the <n/m> streaming device



δ_0 — response period
n — lookback number, an integer
m — averaging factor, a real number

The ratio n/m states the relationship between average pulse periods of the input stream and those of the output stream; e.g., for an input pulse train with a period of $20\delta_0$ between pulses, the output signal of a <3/6> streaming device is a pulse train with a period of $10\delta_0$ between pulses. When a frequency is meaningful, as with a pulse train, the output signal has a frequency that is m/n times the frequency of the input signal. If a pulse train is input into a <3/6> streaming device, the output pulse train will have twice the frequency. Adjustable values of m and n mean that, within a range of possibilities, the streaming device can serve as a frequency multiplier.

Figure 23 shows examples of activity of streaming devices. Fig. 23.a. shows an illustrative input pulse stream where an early regular period becomes irregular in the central portion of the figure, and then regularity re-appears at the end of the figure.

Fig. 23.b. superimposes the input pulse stream of Fig. 23.a. with the stream of output pulses from the <3/3> streaming device. The image of the input pulse stream is flipped for the viewer's convenience. The method of construction of the output pulse stream is shown in Figure 24.

In Figure 23.b, the output pulse stream correlates to the input pulse stream, in an approximate way, with a delay of 2-3 pulses. The two streams have close to the same average period, but there is a "smoothing" of irregularities in the output stream. Similar smoothing appears in "30-day moving average" charts in stock market reports, smoothing the daily ups and downs in price.

Figure 23: pulse streams in streaming devices

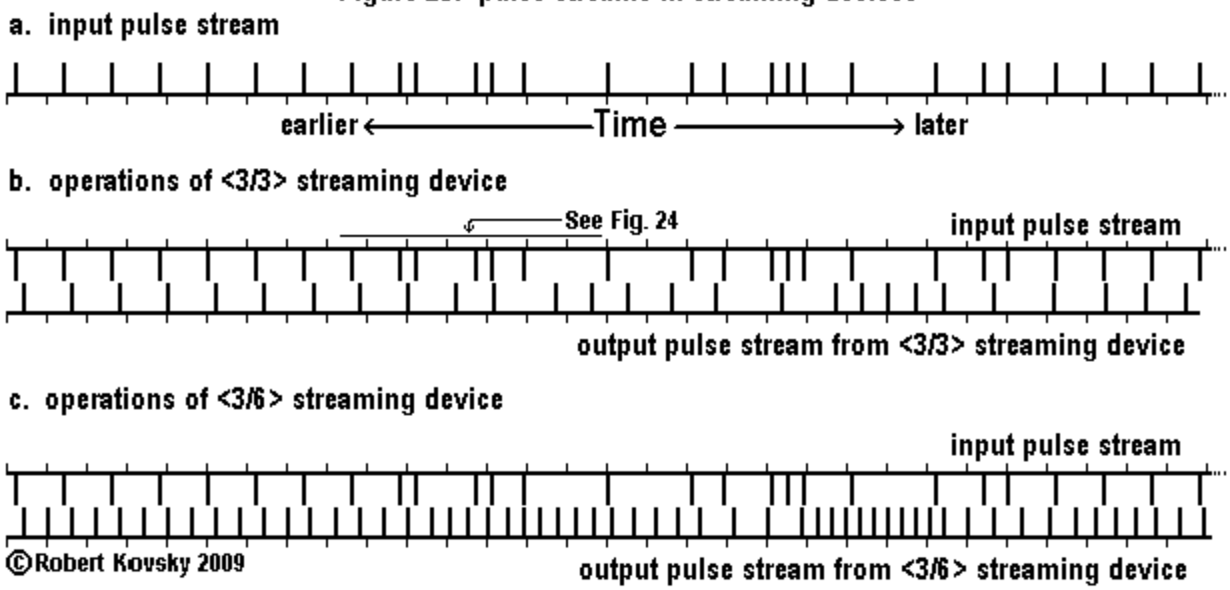


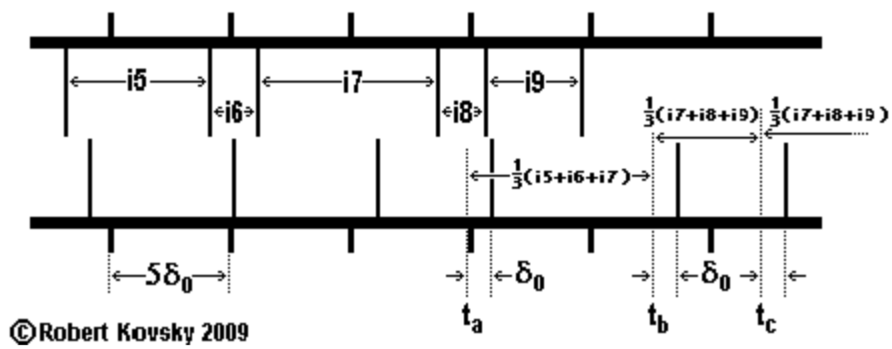
Fig 23.c shows the stream of output pulses of the <3/6> streaming device with the same input pulse stream as that shown in previous images. The output pulse stream still correlates to the input pulse stream but with about half the period or about twice the average frequency of pulses.

In a general way, m can, in principle, take on any real value from a value close to 0 to a very large value, including fractions, decimals, irrationals and so forth. (In contrast, n is an integer.) A purpose of the design is to provide a means of multiplying or dividing a pulse frequency by a given ratio, namely, m/n. For an ideal pulse train, the multiplied streaming is exact. Variations are followed with a short delay. Irregularities are smoothed, a capacity that can be used to modify an irregular signal so as to make it suitable for a device, like a frequency analyzer, that needs a highly regular input.

Detailed examination of the internal operations of the <3/3> streaming device shows the steps in performing a calculation that "looks back" at the 3 most recent input pulse periods and that uses the average of those input pulse periods as the period for the next output pulse.

Fig. 24 shows detailed operations of the <3/3> streaming device for the part of the pulse stream indicated in Fig. 23.b. In the input pulse stream, the time intervals marked "i5" through "i9" are the focus of interest; the numbers 5, 9, etc. are arbitrary. Let tij symbolize the time of arrival of the j^{th} input pulse. Let ij symbolize the period between the $(j–1)^{th}$ input pulse and the j^{th} input pulse, that is, ij = [tij – ti(j–1)]. For a device with a lookback specification of n, there is a memory register with n units that holds the n values of ij for the most recent n+1 pulses.

Figure 24: detailed operations of <3/3> streaming device



In addition to inheriting the response process and response clock of the primal timing device, the streaming device has a "streaming process" and a "streaming clock." (Recall the two-pulse trigger device with its "rousal process" and "rousal clock.") The streaming process operates in a cycle that is set forth as follows.

Let us enter the cycle of the streaming process just as the streaming clock triggers the (primal) response process that produces the next output pulse after the passage of δ_0; e.g., enter at t_a, t_b or t_c in Fig. 24. The streaming clock immediately starts again at 0. Performing the algorithm set forth below, the streaming process calculates the period between the time of the trigger that just occurred and the time of the next trigger, e.g., the period between t_a and t_b. Presumably the streaming process can perform this task in less than τ_{MIN}. The streaming process sets the streaming clock to run for the period so calculated and then to trigger the response process of the device. When that trigger occurs, we have completed a cycle of the streaming process, which proceeds to repeat the cycle.

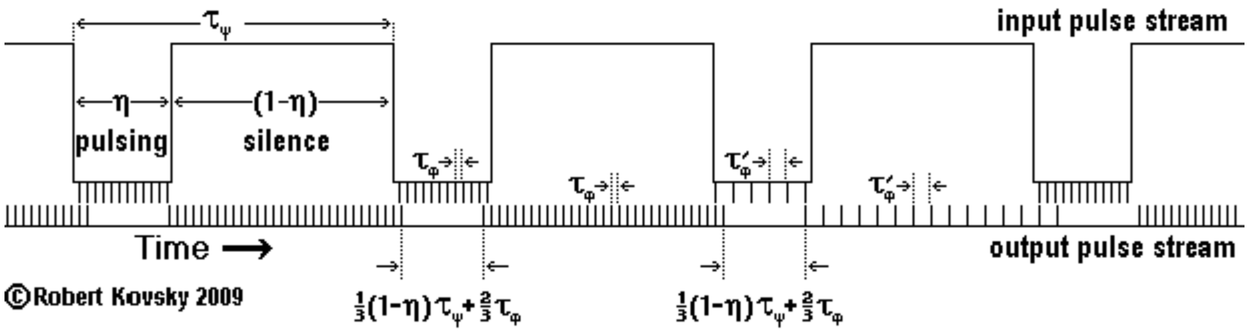
As for the algorithm, begin with operations shown in Figure 24: an output trigger occurs at time t_a and an output pulse is discharged after the response period δ_0. As of t_a, the streaming process "looks back" at the most recent three periods between pulses. As of t_a, the most recent three periods are i7, i6 and i5 (i8 is in progress and incomplete). The "average" of these periods is ⅓(i5+i6+i7) and this time period is added to t_a so as to set the streaming clock to t_b, when the next output pulse is triggered. At that time, a similar calculation is performed with the periods that are then most recent, namely, i7, i8 and i9 and the average is ⅓(i7+i8+i9). No additional input pulse occurs before the discharge at t_c, and the period between t_c and the next trigger is ⅓(i7+i8+i9), repeating the prior processing.

4. Modified streaming devices convert signals between forms:

a. Converting pulse bundles into a sequence of pulse trains.

Figure 25 shows operations of a streaming device when the input pulse stream is a sequence of pulse bundles. The organizational period of the input bundles, τ_ψ, is the same for all bundles. There is one bundle where the pulsing period τ_φ (denoted τ_φ' in that bundle) is larger than in the other bundles, which all have the same τ_φ.

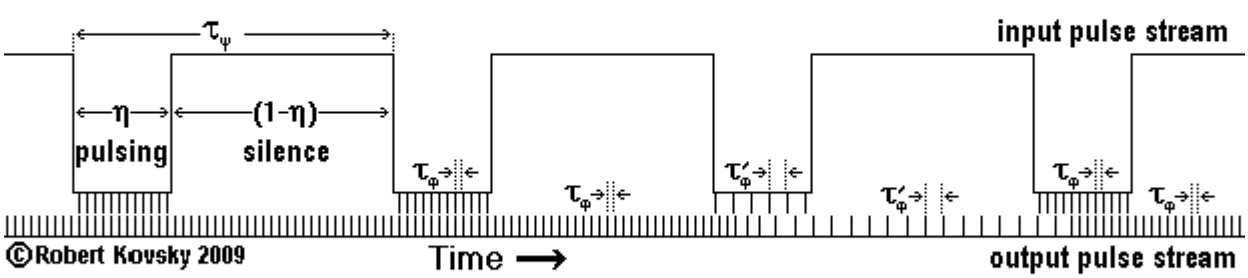
Figure 25: original <3/3> streaming device processing pulse bundles



A prominent feature of the output pulse stream in Fig. 25 is the large silent period that occurs during each input bundle. Each large silent period in Fig. 25 is the same size, $\frac{1}{3}(1-\eta)\tau_\psi + \frac{2}{3}\tau_\varphi$. The large period occurs because the "silent" part of the pulse bundle – $(1-\eta)\tau_\psi$ – is treated like a period between pulses by the algorithm.

There are devices, e.g., the Ear for Pythagorean harmonics, where a more uniform pulse stream is preferable to the form shown in Figure 25. Figure 26 shows operations when the original <3/3> streaming device is modified so that the algorithm ignores the silent part of the pulse bundle. The modification calls for limitation on recognition of the period between pulses based on the size of the period. There is a "maximum τ," or maximum period between pulses that will be recognized, denoted τ_{MAX}; if a period between pulses is greater than τ_{MAX}, that period will not be recognized or used in calculations. The result is a "τ_{MAX}-modified streaming device," with operations for the <3/3> device shown in Figure 26. It is as if the last pulse of a predecessor input bundle merges into the first pulse of its successor input bundle and the silence in the output is "filled in" from the prior output until the device catches up.

Figure 26: τ_{MAX}–modified <3/3> streaming device processing pulse bundles



The τ_{MAX}-modified streaming device converts input pulse bundles into a continuous output pulse stream made up of segmented output pulse trains with continuous transitions, a highly regular signal. In the modified <3/3> streaming device, each segment in the output pulse stream has a fixed pulse period based on the average occurring in the most recent bundle. Near the beginning of an input pulse bundle, the pulse period of the output stream adjusts to the input pulse periods.

The form of the signal has been converted from pulse bundles to a continuous pulse stream; but one chief item of content, the pulsing period τ_φ and its variations, has been preserved. The organizing period, τ_ψ, can perhaps be extracted from the pulse stream, at least approximately. On the other hand, one item of content, the value of η, has been irretrievably lost.

b. Converting pulse bundles into related pulse bundles.

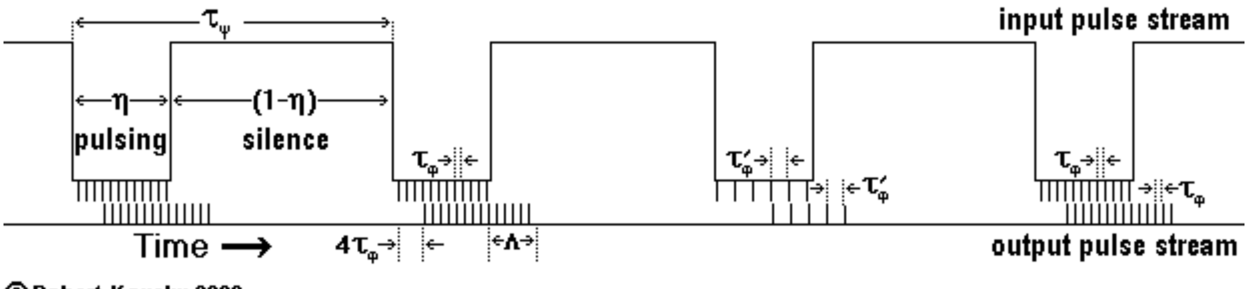
In the device that converts input pulse bundles into related output pulse bundles, a single organizational period, ψ, governs both kinds of bundles, with a delay in the output stream. The <n/m> ratio operates as in Figures 22 *et. seq*. The output τ_φ is (n/m) times the input τ_φ, using the averaging process and allowing for a range of ratios.

The device should have a single form of operations for pulse streams and pulse bundles. For a very long or "infinite" input bundle, the device should perform like the original streaming device performs with an uninterrupted input stream. The performance should be approximately continuous as the organizational period, τ_ψ, is treated as a variable and traverses a range, becoming smaller than "very long," then smaller still and finally reaching a minimum. Performance should be approximately continuous as other specifications vary in their ranges.

The first step in modifying the streaming device to make it suitable for such bundled operations is to add an on-off switch that operates like a gate modulation discussed in point C.3.a. The on-off switch controls the calculator of the streaming device. When the calculator switch turns from "on" to "off," the contents of the calculator are erased and the calculator goes into an "off" condition. The condition of the calculator is "normally off." An input pulse turns "on" the calculator switch, but only for a certain period of time, Λ. After the period Λ passes – and unless there is another input pulse – the calculator switch turns off. To keep the calculator "on," the input stream must have a continuous sequence of pulses with intervening periods of not greater than Λ. In other words, $\tau_{MAX} = \Lambda$. If all input pulse periods are less than Λ, the device operates like the original streaming device. If any $\tau > \tau_{MAX}$, the calculator switch turns off.

Figure 27 shows the resulting output pulse stream when the foregoing "gate-modification" is made to the <3/3> streaming device, with τ_{MAX} or $\Lambda = 24\delta_0$. Output pulses start after the fourth input pulse in a bundle and continue until Λ after the last pulse in the input bundle.

Figure 27: Gate–modified <3/3> streaming device processing pulse bundles



The device shown in Figure 27 should be satisfactory for some purposes. Other purposes may call for processing with an exactitude comparable to that of the summation device, where an arithmetic expression exactly relates the number of pulses in input bundles to the number of pulses in output bundles. There are two significant shortcomings in the operations of the gate-modified device shown in Figure 27, from the perspective of mathematical exactitude. First, to operate the <3/3> streaming device, the calculator needs four input pulses to make the first calculation; and the beginning of each output pulse bundle is delayed until after the occurrence of four pulses in the input bundle. Second, at the other end of the output bundle, the modified device needs the period Λ to detect the end of the input pulse bundle; and the output of the pulse bundle continues until this period elapses, adding a "tail" of this length to the output pulse bundle. These features can be addressed, at least partially, by further modifications.

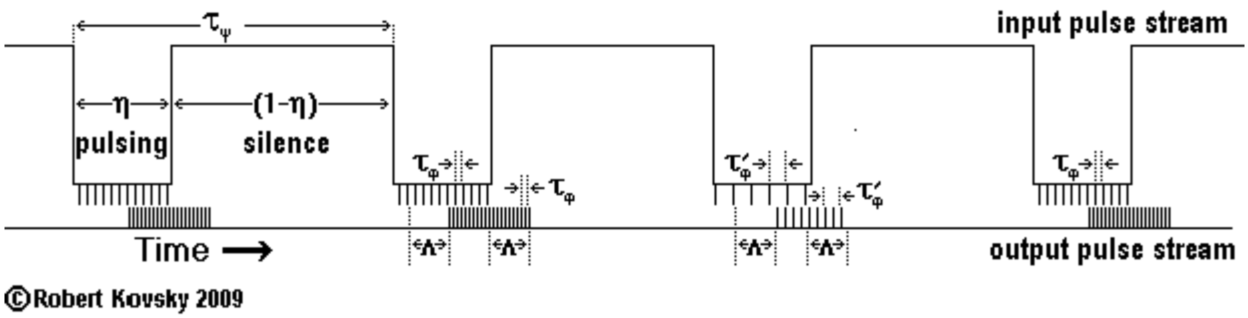
A modification of the start-up of the calculating process will get a faster response at the beginning of the bundle. In such modified process, the first output pulse is triggered immediately upon arrival of the second input pulse. The first output period is then set on the streaming clock and it is equal to the first input period. This is the activity of a <1/1> streaming device. When the first output period has passed, the second output pulse is triggered and the streaming process calculates the next or third output pulse. First, the streaming process attempts to operate as a <3/3> streaming device. If there are not sufficient entries in memory to operate as a <3/3> streaming device, the streaming process attempts to operate as a <2/2> streaming device. If there are not sufficient entries in the memory to operate as a <2/2> streaming device, the streaming process operates as a <1/1> streaming device, which is known to be possible because it has just occurred. The streaming process similarly adapts to any short memory as needed in further calculations. Please note that, for a pulse bundle with uniform τ_φ, all <n/n> streaming devices produce identical output after the initial delay.

The foregoing modification means that the output pulse bundle will start close to the time that the input pulse bundle starts, with a delay of only one pulse period, and with a loss of one pulse.

It is also possible to reduce the end of the pulse bundle. One modification is to lengthen the output apparatus: add a "delay" of Λ (see point E.3) at the present output and then place a normally closed gate at the final step of the lengthened output assembly. The gate is controlled by a copy of the input pulse and has the same Λ as the gate previously introduced. That is, after the last input pulse has been received, and after an additional Λ passes, the output gate closes and the last Λ of the output pulse stream will be left inside, making the size of the output pulse bundle close to that of the input pulse bundle (possibly losing one pulse). Please note that the entire output stream is delayed by Λ, which loses the advantage from a faster startup.

Figure 28 shows the results of the foregoing modifications with a systemic delay in release of output pulses of $\Lambda = 24\delta_0$. The first pulse in the output stream occurs immediately after the second input pulse, plus Λ. The output stream shuts off after Λ has gone by without an input pulse. Figure 28 shows operations of a fully modified <3/6> streaming device.

Figure 28: fully–modified <3/6> streaming device processing pulse bundles

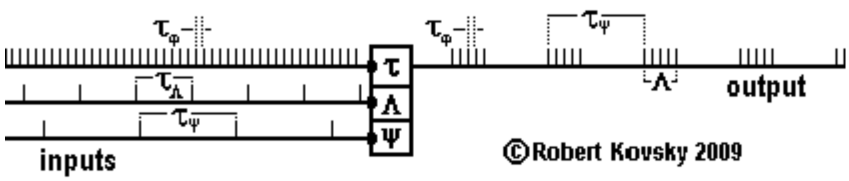


Other than the delay and frequency multiplication, if any, the chief discrepancy between input bundles and output bundles in Fig. 28 is that output bundles are systematically shortened by one or two pulses from the number in the input bundle. This discrepancy could be largely corrected by one additional input pulse period, delaying the turning “off” of the calculator switch at the end of the Λ period by an additional period of τ_φ calculated from recent input pulses. With such corrections, the processing shown in Figure 28 would be superior to that of Figure 26 for purposes of pulse counting and, under suitable controls and conditions, could approach idealized, exact mathematical processing.

c. Generating pulse bundles from pulse trains.

The final case of conversion between ideal signal forms is the conversion of pulse trains into pulse bundles. This is accomplished by means of a pulse bundle generator shown in Figure 26, where three pulse trains are needed to define the bundles, one each to specify τ_φ, τ_ψ and $\Lambda=\eta\cdot\tau_\psi$ (Fig. 21). The values of periods τ_φ and τ_ψ in the output stream are based on those in the input streams. Primal operations generate output from the τ_φ input. The τ_ψ input opens a normally-closed gate so that each bundle starts immediately after the ψ pulse. The length of time that the gate is open – Λ – is calculated algorithmically.

Figure 29: pulse bundle generator



The calculation of Λ from the periods of τ_Λ is largely arbitrary. For purposes here, suppose that Λ is to vary from Λ_0 to $M\cdot\Lambda_0$ where M is less than (τ_ψ / Λ_0). Let the frequency of pulses onto the Λ input of the pulse bundle generator be denoted by $\nu = (1/\tau_\Lambda)$ and let ν vary from ν_0 to $N\cdot\nu_0$. The idea is that ν varies from ν_0 to $N\cdot\nu_0$ and that the variance in ν controls the variance in Λ from Λ_0 to $M\cdot\Lambda_0$. The value of ν may be taken from the most recent input period or may result from operations of a module that acts like a streaming device (point D.3), producing an average value.

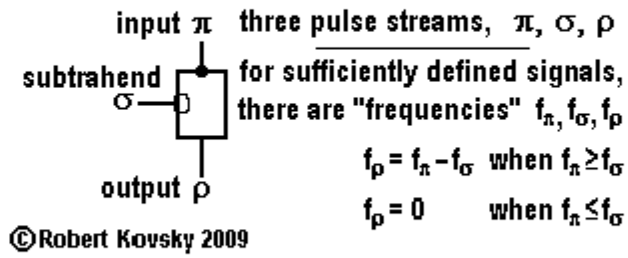
Then: $\Lambda = \Lambda_0 + (\nu - \nu_0) \cdot [(M-1) \cdot \Lambda_0] / [(N-1) \cdot \nu_0]$.

E. Differences and Balances in Timing Device Systems

1. Difference devices and balancing units.

Figure 30 shows the schematic design element for the difference device and defines its operations as a "frequency subtraction device" when signals are "sufficiently defined." There are three signals, pulse streams π, σ and ρ. Pulse stream π is the input to the difference device; σ – called the "subtrahend" – is like a stream of modulation pulses; and ρ is the resulting output stream. If sufficiently defined, each signal has a "frequency," f_π, f_σ and f_ρ respectively and $f_\rho = f_\pi - f_\sigma \geq 0$.

Figure 30: difference device



Production of pulses requires a certain relationship between periods in the input and subtrahend streams, namely, that $\tau_\pi \leq \tau_\sigma$, where τ_π is the period between pulses in the π pulse stream and τ_σ is the period between pulses in the σ pulse stream. More precisely, there is a phase transition at $\tau_\pi = \tau_\sigma$. On one side of the transition, one phase is "operational," namely, when $\tau_\pi \leq \tau_\sigma$, and the other phase is "silent," namely when $\tau_\pi \geq \tau_\sigma$. To maintain the operational phase, no more than a single subtrahend pulse can occur between any two input pulses ($\tau_\pi \leq \tau_\sigma$).

If the signals are sufficiently defined or regular – so that the concept of frequency can be applied, the following is the full statement of operations:

$f_\rho = f_\pi - f_\sigma$ when $f_\pi \geq f_\sigma$;
$f_\rho = 0$ (silence) when $f_\sigma \geq f_\pi$.
When $f_\pi = f_\sigma$, $f_\pi = f_\rho = 0$. The two definitions coincide at the transition point.

What qualifies as a "sufficiently defined signal" depends on the function of the resulting output stream: for some functions, hardly any definition is required and it is sufficient that an average be fixed or approximately so; other functions require signals that are quite close to an ideal pulse train. Compare summation devices and frequency detectors discussed in point D.1. Note that irregular signals can be "smoothed" through the use of streaming devices.

The essence of operations of the difference device is that the device performs subtraction by a process of "cancellation" of pulses – each pulse in the σ pulse-stream canceling one pulse in π pulse-stream – and then passing the diminished π pulse-stream signal through as output ρ. The number of pulses in ρ is equal to the number of pulses in π minus those in σ. See point C.1.b and Figure 7 for an example of cancellation of pulses in a string of coupled timing devices.

The device works for ideal pulse trains as inputs but generates an irregular output. That is, if π and σ are ideal pulse trains, ρ is irregular. As in the summation device, where the same feature appears, ρ maintains an average period that is close to a fixed value. The output stream, although irregular, has a repetitive period that is the product of the input period and the subtrahend period. Details are shown in connection with Figure 32.

Figure 31 shows an important use of the difference device, in two versions of "balancing units." In each version, two difference devices are hooked up to two pulse streams (f and g) that serve as input and subtrahend, one each to each difference device. For two different pulse streams, one difference device will operate at any given moment and one output line will carry a signal; the other difference device will be silent. If the two pulse streams are identical, both lines will be silent.

Figure 31: balancing units

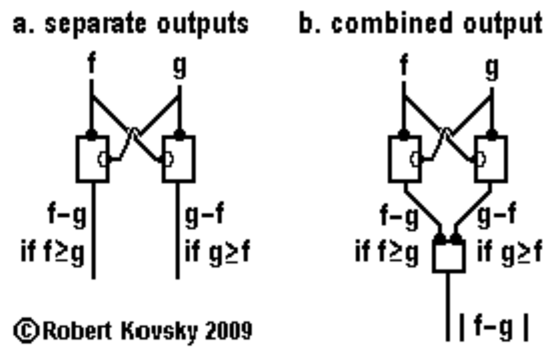


Figure 31.a shows a balancing unit with separate outputs. Suppose that the frequency of pulses through f is greater than that of those through g and, therefore, that the f–g output is active while the g–f output is silent. Then suppose that the frequency of pulses through g is gradually increased. When f=g, both outputs are silent. As g continues to increase, the g–f output is

active while the f–g output is silent. This transition is a phase transition as to each output because on one side of the g=f line, one line is active and the other silent; but these conditions are reversed on the other side of the g=f line. However, this transition is of a "smoother" kind than, e.g., the transition of point B.2, dealing with "cycles" made up of primal timing devices.

In the balancing unit shown in Figure 31.b, the outputs from the two difference devices are inputs to a timing device that operates according to the "one-pulse trigger" rule. (Point C.1.) At any time, no more than one difference device generates input to the simple timing device. The possibilities are combined in the formulation | f–g |, denoting the absolute value of f–g.

More detailed discussion follows.

In early designs of "subtraction devices" that were based on strings of coupled timing devices, a "subtraction" occurred when one pulse canceled another pulse within the string. See point C.1.b and Figure 7. Such designs had a conceptual foundation in a physical model – called the "Virtual Energy Model" – designed to be congruent with biochemical processes (which proceed at diverse time rates). The Virtual Energy Model is set forth in § 4 of the Quad Net paper. See, e.g., Image 49 in the Quad Net paper and surrounding text for the foundational concepts of the "one-pulse trigger" rule and the "two-pulse trigger" rule.

Convolution devices, e.g., the streaming devices discussed in points D.3 and D.4, are not based on the Virtual Energy Model. Rather, a "calculator" is introduced, with an "algorithm" that is foreign to Quad Net principles. The advances that are made possible by convolution devices overcome any scruples about introducing such foreign principles. My approach is that of an "unscrupulous opportunist." [A. Einstein, quotation in P. Feyerabend, *Against Method* (3d. ed. 1993) at 10, n.6.] What is required in developing the system is that older methods and new methods be organized so that they work together in an integrated way.

The current design for the difference device combines pulsational and algorithmic methods. Algorithmically, the difference device uses a "counter" that can take on values of 0 and 1. This value is denoted c=0 or c=1. "Positive pulses" come in the π pulse-stream and "negative pulses" come in the σ pulse-stream, changing the value of the counter according to stated rules. Pulsationally, the difference device inherits the primal response process – with δ and β – from the primal timing device. If there are no negative pulses, the device's operations are very close to those of a primal timing device.

To show the operations, start with the counter at value c=0. The following rules apply: The arrival of a negative pulse does not change the counter when it is set at c=0. The arrival of a positive pulse changes the counter from c=0 to c=1. If c=1 and a positive pulse arrives, the responding process of the device is triggered (leading to an output pulse) and the counter stays at c=1. If the counter is at c=1 and a negative pulse arrives, the counter is changed to c=0.

As an additional feature of the difference device, there is another clock running while the counter is at c=1. Such clock, called the "on-clock," operates like the rousal clock of the two-pulse trigger rule and the Λ clock in a normally-open gate timing device. (See points C.2 and D.3.) The on-clock runs for a specific amount of time and if no new pulse arrives, it turns the counter to c=0, thus avoiding lingering effects from occasional pulses. The period of the on-clock is relatively large.

While operations are productive, the foregoing device will generate an output stream that contains a number of pulses equal to the difference between the number of pulses in the input stream and the number of pulses in the subtrahend stream. In terms of frequency, output = f – g.

Figure 32 shows illustrative operations of a simple example, where $\tau_\pi = 5.0\delta_0$ and $\tau_\sigma = 7\delta_0$. The device's response process is triggered – at moments marked with an asterisk below the time line – by the arrival of two positive pulses without an intervening negative pulse. The resulting pulses constitute the pulse stream τ_ρ, which is irregular but with an average period of $(35/2)\delta_0$.

Figure 32: operation of the difference device

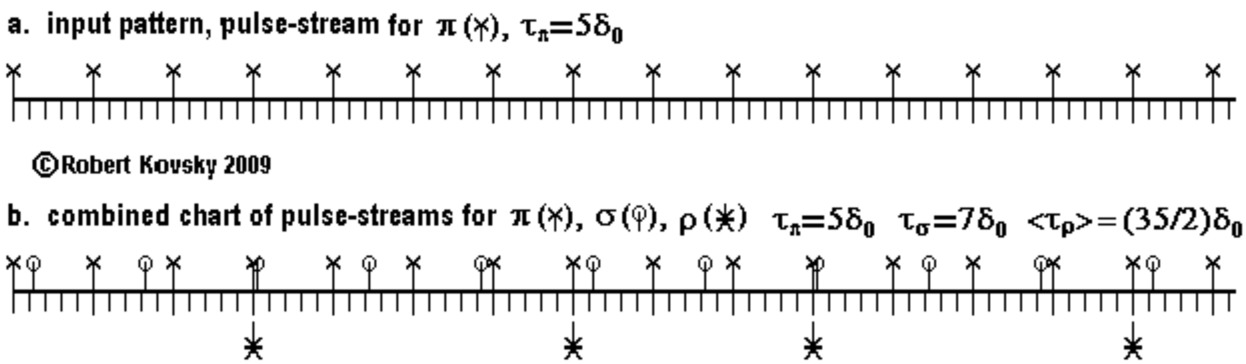


Figure 32.a shows input pulses (x) alone. Figure 32.b includes the subtrahend pulses (○) and shows the resulting output pulse triggers (*). The chart shows two full cycles of activity (at $35\delta_0$ per cycle) plus the startup operation; there are 14 positive pulses, 10 negative pulses and 4 resulting pulses: the device performs 14 – 10 = 4.

We consider the variation in the output stream that results from a controlled variation in the subtrahend stream – denoted "g" – while the input stream – denoted "f" – remains fixed. Suppose that there is a process (the "g period reduction process") during which the period between pulses in g, namely, τ_σ, is reduced from "very long" (very low frequency) until it reaches equality with the period between pulses in f, namely, τ_π. At one extreme, when there is no signal in g at all – the period of g is infinite – the device behaves like a primal timing device, except for startup loss of one pulse and a longer delay in tracking changes in the input stream.

When g or subtrahend pulses have a period less than infinite but much greater than that of f, the result is an output that has a periodic absence of a pulse because of cancellation occurring in the difference device. Except for such periodic absence, the output reproduces f. Such an absence of a pulse in an otherwise regular pulse train is called a "hole." In other words, during the g period reduction process, and with an ideal pulse train as input to f, output starts as an ideal pulse train that reproduces f; and then departs from the ideal by the occasional removal of a pulse or, alternatively, creation of a hole. Holes are created at first at large distances from one another, and the period between holes is an approximately fixed quantity equal to the period of g pulses.

As the g period reduction process proceeds, that is, as g pulses arrive more frequently, the distance between holes in the output stream shrinks. At first, perhaps, there are 20 positive pulses between holes; the distance shrinks from 20 positive pulses to 10, then to 5, 4 and 3. Throughout this shrinkage, the changes are stepped but otherwise smooth. Indeed, smoothly stepped shrinkage continues even after the number of un-matched positive pulses between holes falls below 1, so that holes appear one after another without intervention. Figure 32 is an example of this operation. It is when the number of positive pulses between holes falls towards 0 that the system approaches the limit allowed within the constraint $\tau_\pi \leq \tau_\sigma$. When nothing but holes remain, $\tau_\sigma = \tau_\pi$ and the output is silent.

Throughout the g period reduction process, the output is changing in a regular, almost continuous, way, with increasing density of holes and decreasing number of triggering pulses, as the ratio of τ_σ/τ_π traverses a path from ∞ to 1. The broad operating regularity of the difference device makes it especially useful.

2. Engineered organisms that move and sense from a condition of balance.

This sub-section sets forth designs for simple if impractical engineered organisms and their supposed primitive engagements with reality. "Impractical," means that avoidance of mechanical issues that actually beset small organisms, as are discussed in E. M. Purcell's famous talk on "Life at Low Reynolds Number." The presentation is directed towards investigating principles of balance rather than providing practical designs.

Figure 33: motor unit

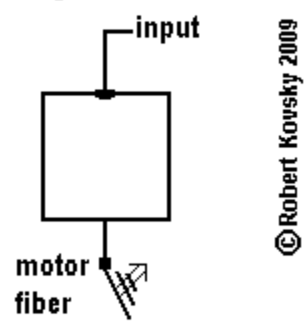


Figure 33 shows a rudimentary two-dimensional motor unit, which converts a timing device pulse into a twitch of a motor fiber. That is, when a pulse comes through the input projection, the motor fiber twitches forcefully in the direction of the arrow. Then the motor fiber returns to its original position.

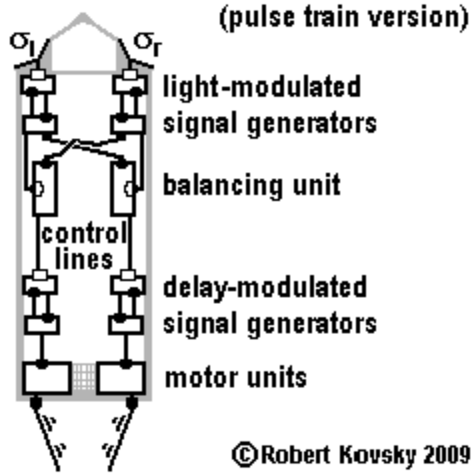
Suppose that the twitching fiber moves like an oar in a watery environment like the ocean, with enough force to propel the engineered organism. Following low Reynolds number principles, the oar is elongated and stiff when moving forcefully but collapsed and limp when returning to the original position.

Motor units of the kind shown in Figure 33 are incorporated in the design for a two-dimensional engineered organism shown in Figure 34, the “pulse train” version. The signals for the motor units are generated in the “delay-modulated signal generators” (see Fig. 16) and have a normal period of $2\delta_0$; but when delay modulation is active – for a period of Λ after a pulse from the balancing unit – the delayed timing device in the signal generator has a response period of $3\delta_0$. Hence, the period between pulses from the signal generator into the motor unit is lengthened from $2\delta_0$ to $4\delta_0$. In sum, while a balancing unit is discharging pulses, the affected motor unit is beating at half the frequency of the unaffected motor unit on the other side. The balancing unit operates so that only one side is slowed at a time and the extent of slowing is always the same. The effect is to turn the engineered organism a bit clockwise or counterclockwise while it generally proceeds in the forward direction.

Senses in Fig. 34 are based on the modulatory principle set forth in the design in Figure 15 with light as the controlling sensation, detected as σ_l and σ_r, with the subscripts indicating left and right. Each light-modulated signal generator produces a signal that approximates a pulse train but with a variable period, shortest when there is no light and longest when light is most intense.

In operations, an imbalance in light sensations will be detected by the balancing unit and pulses coming out of one branch of the balancing unit will slow one delay-modulated motor unit. E.g., if the light is brighter on the left, sensory signals will be slower on the left, pulses will be produced by the left balancing unit and the left motor unit will be slowed. No pulses will come out of the right balancing unit and the right motor unit will operate at full speed. The difference between the average forces generated by the motor units will turn the engineered organism in the counterclockwise direction, tending to remove the imbalance, so that the organism is “facing the light.”

Figure 34: an engineered organism (pulse train version)



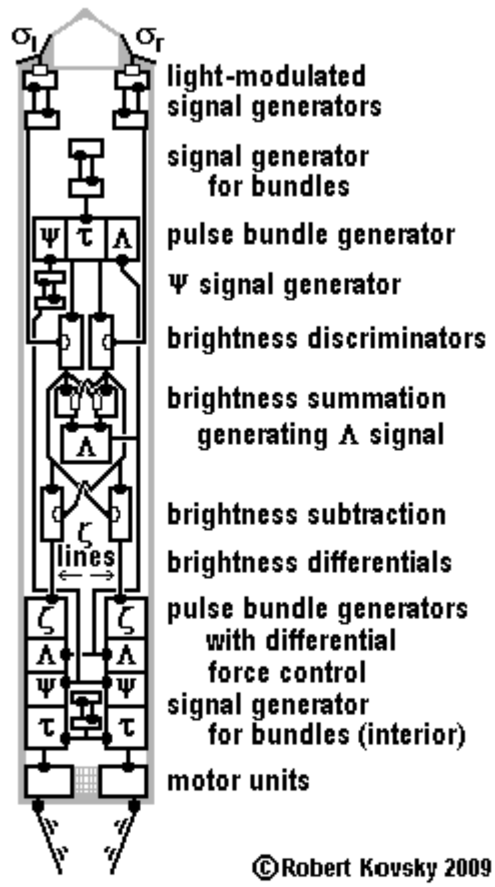
When there is balance, the output of both sides of the balancing unit is a null signal, a condition called “internal silence.” Then, the organism is “heading for the light,” assuming there is a light. If a light is moving from one side to the other, the organism will “follow the light.” The organism acts so that any light becomes “centered” between the sensors. There is a centerpoint of operations around a balanced condition, called “centerpoint balancing.”

“Centerpoint balancing,” “internal silence” (null signals) and “following an external object” make up a fundamental unit in the operations of the engineered organism. I suggest that this unit is a point of origin for the development of additional timing device assemblies, leading towards a psychology based on timing device principles. I suggest that “following” grows into “imitation,” a primal principle of intelligence. (See Piaget, J., *Play, Dreams and Imitation in Childhood*, originally *La Formation du Symbole* (1946).) The psychological unit is “the method of external following through maintenance of internal balanced silence.”

The engineered organism of Figure 34 has distinct limitations, e.g., its incapacity to distinguish between total darkness and flooding light. In full darkness and in full light, and in all perfectly balanced situations, it's always "full speed ahead." A needed improvement is a "brightness control" that will speed up the device in bright light and shut it down in darkness.

The need is met by a "pulse bundle" design shown in Figure 35 with the organism "stretched out" for labeling. Chief new features are pulse bundle generators in the sensory and motor areas, denoted by structures of 3 or 4 boxes, and a "brightness system." The sensory pulse bundle generator operates according to the design shown in Figure 29 and discussed in point D.3.c. The motor pulse bundle generators use the same design, but there is an additional control line, ζ. Pulses through a ζ line cause a lengthening of the period between signal pulses (τ) in the bundle to the motor unit, reducing the force, with faster ζ pulses causing more reduction in force.

Figure 35: engineered organism II (pulse bundle version)



Pulses through a ζ line are generated by the brightness system; frequency of ζ pulses measures the brightness differential between left and right sensors. The brightness system also generates a "summed brightness" signal through the Λ line that controls the size (Λ or η) of a bundle of pulses. Twitches last longer when there is more light.

The design of the motor unit is based on Figures 33 and 34. However, the new motor units are driven by pulse bundles from the pulse bundle generators rather than by continuous pulse streams. If driven with pulse bundles characterized by Λ and τ, the motor fiber twitches with a force that is inversely proportional to τ (proportional to frequency) and that lasts for Λ. See point D.2.

No modification from the design of Fig. 34 is needed as to the light-modulated signal detectors, which deliver a continuous signal to the brightness discriminators (difference devices); an input bundle from the sensory pulse bundle generator is needed to register any modulating effect on a resulting output bundle. Bundles "sample" continuous sensory signals.

A detailed discussion of device operations begins with two signals shared by all three pulse bundle generators, namely, the ψ signal and the Λ signal. The generator for the ψ signal is located under the sensory pulse bundle generator, which it drives; and the ψ line runs to drive the motor pulse bundle generators. The ψ signal organizes bundles from all the generators by means of a single period. An operating principle is that one distinct pulse bundle from the sensory bundle generator will affect exactly one distinct pulse bundle generated in the motor area; further, that the motor bundle will be so effected only by that one distinct sensory bundle: that is, each sensory bundle has a one-one relationship with one motor bundle. This relationship is easily maintained because there is a single period controlling the two rates of bundle production.

All 3 pulse bundle generators also share the Λ signal, which measures total brightness. Different generators treat this signal differently; e.g., in darkness, sensory pulse bundles should have the largest Λ in their range and motor pulse bundles the smallest Λ in their range.

Variations pass from the sensors to the motor units. All six timing devices in the forward sensory region – the light modulated signal generators and the signal generator for bundles – have common primal timing intervals δ_0 and β. If the organism is in darkness, all three signal generators are producing identical signals, "darkness signals," each with the period $\tau_0 = 2\delta_0$ – the "darkness period." The inputs to the brightness discriminators are equal and all the outputs are silent. Production by all three signal generators of darkness signals leads to silence on the Λ and ζ output lines of the brightness system. When the organism is in darkness, brightness is 0.

Light causes brightness signals and the signals measure the light. Suppose that a maximum stimulus lengthens the period of signals from the light-modulated signal generators from $2\delta_0$ to a maximum of $4\delta_0$. There are half the pulses per unit time when the sensor is most brightly illuminated, compared to when it is in darkness.

In Fig. 35, darkness signals provide trigger input to the brightness discriminator and a light-modulated signal is the subtrahend input. The resulting signal, the "brightness signal," is made up of "brightness bundles" produced by cancellation from "darkness bundles," where the number of pulses in a brightness bundle measures the intensity of the light that produced it. A brightness bundle with 0 pulses denotes external darkness and 1 pulse in a bundle denotes the minimally detectible sensation. A maximal brightness bundle – the signal from the brightest light – contains n pulses, where the value of n is a characteristic of the system, e.g., 20 pulses. Using n as a measure, the sensory system on one side can detect and signal n levels of brightness. If the period of pulses signaling maximum brightness is twice that of the darkness, as suggested in the previous paragraph, n is equal to half the number of pulses in an input bundle.

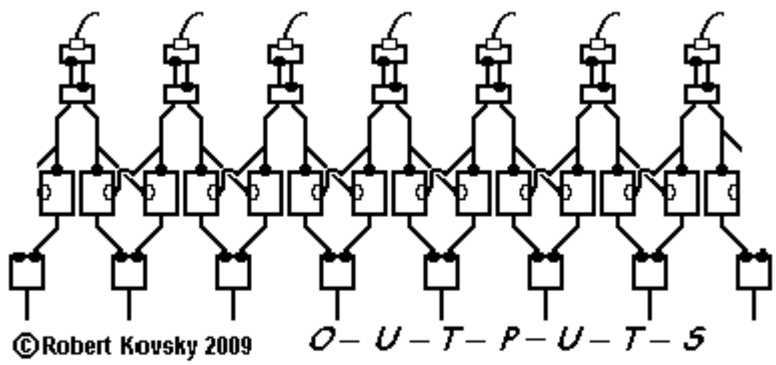
Brightness signals from the brightness discriminators are inputs to a summation device. (Point 3.C.3; Figure 18 *et. seq*.) The output signal measures "total brightness," summed from both left and right sensors. As noted above, the output of the summation device, the Λ signal, is a source signal for the pulse bundle generators, providing control over the η (or Λ) of a pulse bundle.

The method of external following through maintenance of internal balanced silence is carried forward in the pulse bundle version of the engineered organism.

Brightness signals from the two brightness discriminators are inputs to the balancing unit, which performs "brightness subtraction" and produce signals on the ζ line. The balancing unit subtracts the number of pulses in the smaller brightness bundle from the number in the larger bundle. It is this difference, called a "brightness differential," that the motor pulse bundle generator uses to lengthen the period of signal pulses (τ_φ) in the motor pulse bundle, reducing the force of the motor stroke. Suppose that the maximum number of pulses per bundle in a signal on the ζ line is 20 and that the other specifications and constraints on the motor pulse bundle generators are set forth above. The ζ specifications operate so that a brightness differential signal of one pulse per bundle will result in a signal to the motor unit with a period of $2.1\delta_0$, two pulses in the brightness differential signal will change the motor pulse period to $2.2\delta_0$, and the other pairings fit a linear scheme, up to and including the specification that 20 pulses in the most recent ζ bundle (brightness differential) will change the period between pulses in the motor bundle to $4.0\delta_0$. When there is darkness, the ζ bundle is empty and the period between pulses remains at $2.0\delta_0$.

Balancing can be extended from two sensors to an array of sensors, as shown in the design of Figure 36, an array of sensitive hairs and signal generators of the kind shown in Figure 15, combined with balancing units. Activity in an output line identifies force being applied to the sensitive hairs – more precisely, activity in an output line measures a differential in force between adjacent hairs. In other words, the device detects small objects that affect hairs differently. Silence in all the output lines is a signal that there is no perceptible differential of force between any adjoining pairs of sensitive hairs.

Figure 36: array of sensitive hairs and balancing units



The construction method used for the one-dimensional array in Figure 36 can be extended to construct a two-dimensional array operating on the same principles, with a two-dimensional array of outputs.

Arrays of sensitive hairs, like the light sensitivities of the engineered organisms, detect a difference based on a spatial arrangement. In the engineered organisms, light intensity varies when an eye is directed in different directions. In the array of sensitive hairs, the system detects a difference based on relative location in a space-spanning array. In all the systems, the output frequency measures such differences. With the array of Figure 36, the obvious next step is to direct adjoining output signals into another layer of balancing units, for the “second derivative.” All the foregoing suggest a “differential” of the sort encountered in calculus, except embodied in frequency-based signals of timing device systems rather than a geometric form.

3. Delays and matches, echoes and beats.

Figure 37: delay device

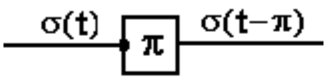


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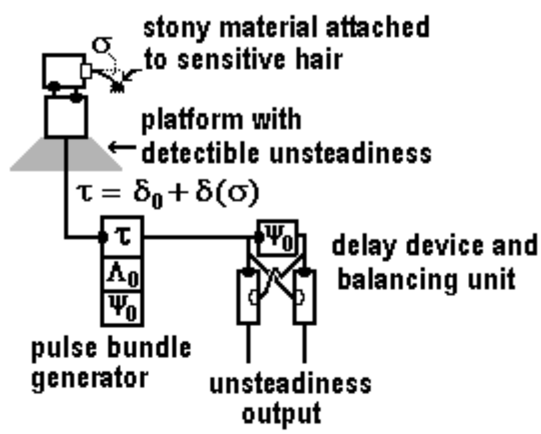
Figure 37 shows a "delay device." Functionally, the output of the delay device reproduces the input signal, but with a specified delay, denoted as π. Of course, every timing device incorporates a delay, at least δ; but an abstract device with an arbitrary delay is useful. Stating the function of the delay device mathematically, if $\sigma(t)$ describes the input signal as a function of time, then the output signal is described by $\sigma(t-\pi)$. If $\pi = 2$, then, at time $t = 5$, the output will be reproducing the input signal that occurred at time $t = 3$.

Figure 38 shows the use of a delay device in an "unsteadiness detector." The amount of delay in the delay device is ψ_0, the period between pulse bundles as produced by the pulse bundle generator. Two pulse bundles, predecessor and successor, are inputs to the two branches of the balancing unit. Hence, the system first balances each pulse bundle against its predecessor bundle and then (after the delay of ψ_0) against its successor bundle. A difference between the number of pulses in two successive bundles appears as a signal in the "unsteadiness output." (See Fig. 32.)

In more detail: all pulse bundles have organizational period ψ_0 and bundle size Λ_0. The signal period within the bundle – τ – is subject to modulation that depends on the position of the sensitive hair, as discussed in connection with Fig. 15. (For the pulse bundle generator, see point D.3.c, Figure 29.)

If the platform supporting the sensitive hair remains stationary, the τ signal into the pulse bundle generator will be fixed. Each bundle will be the same as the previous bundle and the unsteadiness output lines will be silent.

Figure 38: unsteadiness detector



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If, on the other hand, the platform is shaking, the stony material and the sensitive hair will be bouncing up and down. The τ signal into the pulse bundle generator will be highly variable and the number of pulses in a bundle will vary widely, each bundle likely quite different from its predecessor. When a bundle is balanced against its successor, differences will appear becoming pulses on the lines of the unsteadiness output.

There are several lines of development implicit in the unsteadiness detector. First, "stony material attached to sensitive hairs" is suggestive of organs of animals that detect gravity and motion and that enable the organism to orient itself, e.g., organs in the human ear – the utricle, saccule and semicircular canals that are based on "sensitive hairs."

An attractive prospect for modeling is the vestibulo-ocular reflex (VOR). Contrast your ability to keep your eyes on your fingertip, a foot in front of your face, while you move your head in all directions, with your inability to follow the same fingertip while you move it in all directions in front of your face: the VOR performs the corrective function in the first case. The VOR is very useful when running after prey or trying to catch a flying ball. It's operations are largely independent of vision itself, occurring in darkness when vision is inactive.

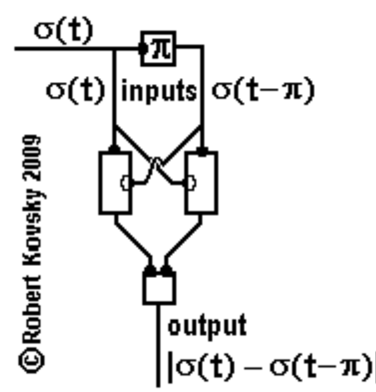
The neural apparatus of the VOR lies in nerve paths between sensitive hairs in semicircular canals in the middle ear that detect movements of the head (the "vestibular" system) and eye muscles that twitch the eye into position. A movement of the head leads to an automatic compensatory twitching of the eyes that maintains the gaze on an object. Activity of the VOR includes a saw-toothed muscular oscillation of the eyeball, "nystagmus." Researchers have mapped the anatomy of the VOR and have identified nystagmus, like the scratch reflex, as a member of a class of conversions from steady input into phasic movements. (Lorente de Nó, R. (1933) *Vestibulo-ocular reflex arc*, Arch. Neurol. Psychiatry 30, 245-291; Szentágothai, J. (1950) *The elementary vestibulo-ocular reflex arc*, J. Neurophysiol. 13, 395-407.)

I suggest that a timing device assembly might model basic activity of the VOR, even perhaps extending to an assembly that incorporates both continuous and phasic forms of activity.

Mathematical observations based on the unsteadiness detector suggest further potential developments.

Let $\sigma'(t) = | \sigma(t) - \sigma(t-\pi) |$ be the combined output of a balancing device that has a delay device of value π between inputs, as in Figure 39, showing a device assembly called a "temporal differential." In general, π is a quantity that might vary. The formulation for $\sigma'(t)$ resembles a time differential in elementary calculus, which complements operations in device arrays that resemble spatial differentials. (See Figure 36.)

Figure 39: temporal differential

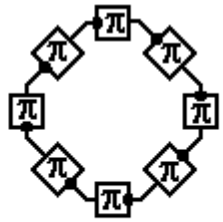


Device operations that resemble differentials for space and time lead towards a timing device version of the seminal relationship d=rt, where d is distance to travel, r is rate of travel and t is time of travel. (See Piaget, J., *The Child's Conception of Movement and Speed*.)

The relationship $\sigma(t) - \sigma(t-\pi) = 0$ defines a class of functions $\sigma(t)$ that are periodic with a period π. Of course, the class includes functions that repeat over and over again. But it also includes a single repetition and a short period of silent output, as in the case of an "echo." As a broader operational definition, signals $\sigma_1(t)$ and $\sigma_2(t)$ "match" one another if they are inputs to a balancing device and the output lines are silent. Matching means that a one-to-one relationship is established between two signals. The match need not be a strict equality. The test is whether there is silence on the output; and some signals that have slight differences between them will produce such silence.

The following designs investigate the possibility of matching two signals that occur at different times as part of a functional memory,

Figure 40: a cycle of delays



The delay device serves as a memory device. Recall the "cycle" of primal timing devices (Figure 2); the cycle form can be adapted for use of the larger device, as shown in Figure 40. In applications, a cycle of n delay devices can maintain a "store" of n pulse bundles, where the pulse bundles might be independent, sequenced or related to one another. The period of activity in the device is 8π and continues indefinitely.

Figure 41.a shows the schematic design of a delay device where π = 36δ and δ is the response period of all 37 timing devices in the device. If the normally closed output control gate is kept open by a signal on the output control line, a input signal arriving at time t_a emerges as output at time t_a + 36δ. Pulses through the memory control line open a gate that is normally closed, with a modulation period of 36δ. While the memory control gate is closed, and presuming no additional input, a pulse bundle of length 36δ circulates within the device.

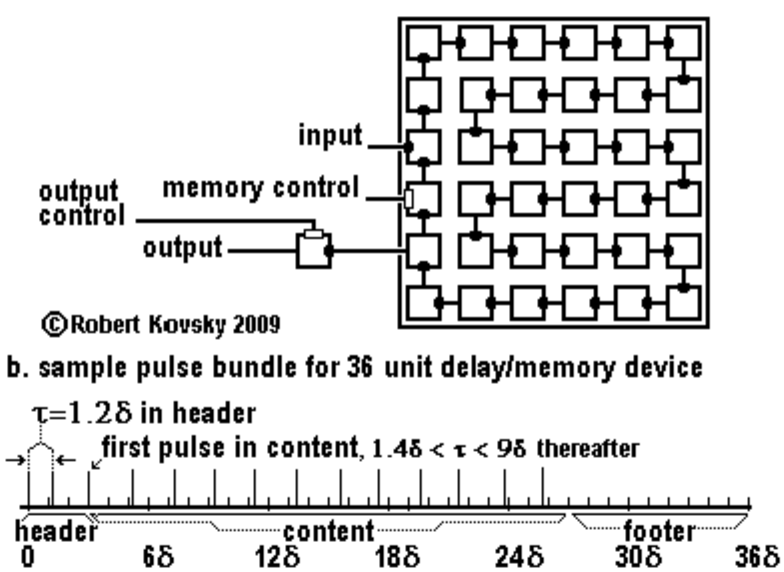
Figure 41.b shows a pulse bundle suited for the 36-unit device.

The pulse bundle is made up of three parts, the "header," the "content" and the "footer." Each part of a bundle has a fixed place and amount of time in the pulse bundle, e.g., 3δ, 24δ and 9δ respectively in Fig. 41.b.

The header is the same for all bundles, with an initiating pulse at 0 and a second pulse at 1.2δ. The 1.2δ period is shorter than all other periods in the bundle. The short period identifies the header to a two-pulse trigger rule device. (Please see Fig. 8; ξ = 0.3δ_0.)

Figure 41: delay device with controllable memory

a. 36 unit delay device with memory cycle



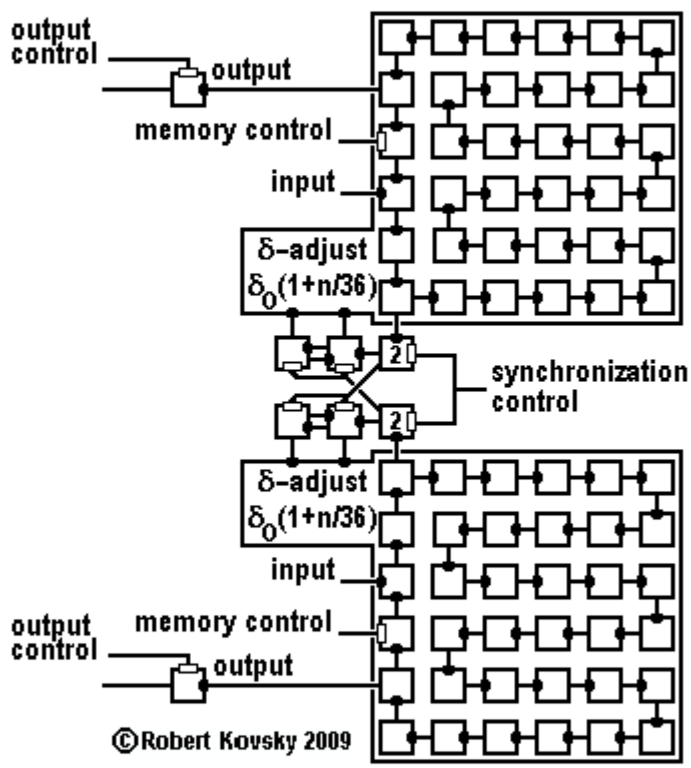
A footer is the longest period in the bundle and concludes the bundle. In Fig. 41.b, the footer is a silent period of length 9δ. The period between successive pulses in the content, τ, is within the constraints: 1.4δ < τ < 9δ, which preserve the identifiability of the header and the footer.

Suppose there are two bundles circulating in two memory devices and the researcher wants to test them for a match by passing them through the two branches of a balancing unit. If two identical bundles reach the two inputs of a balancing unit within τ_{MIN} of each other, the output of the balancing unit will be silent. For the bundles of the kind shown in Figure 41.b, τ_{MIN} = 1.2δ, the header period.

Figure 42 shows a system for synchronizing two pulse bundles in adjacent mirror-image delay/memory devices. The memory devices have been modified by the addition of a "δ-adjust" feature. All individual devices in a memory device share the same δ. The δ–adjust feature turns the collective δ into a variable with a value greater than a fixed value, δ_0. Any value greater than δ_0 means a slowing down of a bundle; and the greater the value, the more slowing. The possible values of δ are stated by the formula δ · (1+n/36) where n is 0 or an integer between 1 and 36. If n=0, there is no slowing. If n=1, the slowing is equivalent to 1 individual timing device per revolution, compared to an un-slowed bundle. If n=36, the relative slowing is 36 timing devices or one complete revolution. In the synchronizing system, only one memory device is slowed at a time and the δ of the other memory device remains at δ_0.

The synchronization control system has two mirror-image branches; each branch has a two-pulse rule timing device triggered by a projection from the memory device and a signal generator that is started by a pulse from the two-pulse timing device. Each two-pulse timing device has a normally-closed gate that is opened by a pulse through the synchronization control line for a period of Λ = 36δ. A pulse from one two-pulse timing device will close normally-open gates in the other branch and prevent that other branch from discharging pulses for a period of Λ = 36δ.

Figure 42: synchronizing bundles in memory devices



The system requires two cycles to perform the synchronization, a first detection cycle and a second execution cycle, during which one bundle is slowed. First, two (unsynchronized) bundles are loaded into the two memory devices. Then, a pulse appears on the synchronization control line, starting the detection cycle and opening normally-closed gates on the two-pulse trigger rule timing devices for Λ = 36δ.

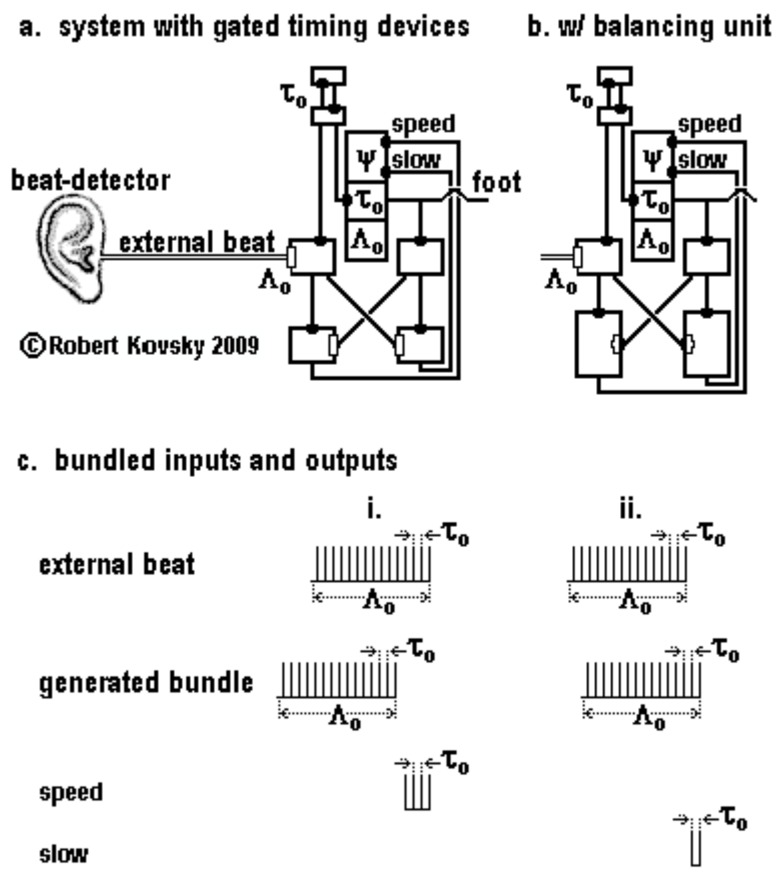
The rousal period of a two-pulse trigger rule timing device, ξ=1.3δ, makes it responsive only to a header. The first header to pass adjacent thereto starts one signal generator and blocks the other signal generator. The active signal generator runs until its gates are closed by a pulse from the other two-pulse trigger rule timing device, after the adjacent passage of the header of the second memory bundle.

The number of pulses sent by the signal generator into the adjacent δ–adjust unit during the detection cycle will be approximately equal to the number of memory device timing devices lying between the two headers, e.g., 5 pulses will signal that header 1 is "five timing devices" ahead of header 2 in the comparable memory devices. The δ–adjust feature uses that number of pulses to calculate the adjusted δ for the execution cycle. It appears possible to meet the goal of

synchronization within $\tau_{MIN} = 1.2\delta_0$. Repeated synchronizations may be employed.
A similar synchronization subsystem is used in a design for "following the beat" using gated timing devices, shown in Figure 43.a. A slightly different design with a balancing unit is shown in Figure 43.b. "Following the beat" systems aim to model activity of musicians playing in an ensemble where a rhythmic leader – e.g., a drummer – establishes a dominant, simple pulse-rhythm called "the beat," The beat may be metronomic or it can have a range of periods that the leader controls. A musician's ear can detect a changing beat. The task is easy when the beat is the loudest sound and other sounds are repetitively organized around the beat. Many musicians unconsciously tap a foot to the beat.

I suggest that there is something like an "internal beat generator" in a musician's brain, modeled by a pulse bundle generator and denoted by three-box structures in the designs shown in Figure 43. It is the internal beat generator that sends the "tap" signal to the musician's foot, rather than a signal based on what is being heard. If a band's drummer should hiccough and miss a beat, the guitarist will tap his foot anyway. In other words, the internal beat signals are different from signals produced by the "beat-detector" that is responsive to the environment and that produces a pulsation each time a beat is heard, a pulsation I call the "external beat."

Figure 43: following the beat



While the musician's internal beat generator is synchronized with the external beat, the musician is "following the beat," meaning: coincidence of signals during much of the time, a slowing down of the internal beat generator if the external beat falls behind and, conversely, a speeding up of the internal beat generator if external beats arrive faster .

The period ψ between internal beats is the organizational period of pulse bundles produced by the generator. Such bundles are of size Λ_0, same as the modulation period for the normally closed gate that shapes "external beat" bundles for comparison with generated bundles. All bundles share τ_0. Comparison generates signals that are sent on "speed" and "slow" lines to the pulse bundle generator, controlling adjustments to ψ in the style of Figure 42. $\psi' = \psi \pm n\tau_0$. Each bundle leads to a new adjustment.

For detailed analysis, begin with a fixed external beat and with an internal beat generator that is synchronized with the external beat. Synchronization means silence on the speed/slow control lines accompanied by foot-tapping that shows an active system. If the period of the internal beat generator fluctuates, corrective pulses appear on the speed/slow control lines. If the external beat is changed through a slow but directed variation, e.g., growing steadily faster, signals will be generated on the appropriate control line, e.g., on the speed line that tells the internal pulse bundle generator to speed up. Key signals in such a case are shown in Figure 43.c.i, where the bundle generated by the external beat arrives at the comparison devices a bit ahead of the bundle generated by the internal pulse bundle generator and a signal is generated by the comparison devices and sent on the speed control line to the pulse bundle generator for adjustment of ψ. In the second case, shown in Fig. 43.c.11, similar to that in 43.c.i, the generated bundle arrives before the external beat bundle and the generator is instructed to slow down. The difference in arrival times is less in the second case and calls for less corrective adjustment.

Comparison of the gate normally-closed system in Fig. 43.a with the balancing unit system of Fig. 43.b shows overall equivalence in results. Both systems will produce the bundled inputs and outputs shown in Fig. 43.c. There are however, differences in the details of operations. E.g.,, variations in the signal period within a bundle can have consequences for operations in the system of Fig. 43.b but not that for those of Fig. 43.a.

A difference in arrival times of beat signals in Fig. 43.c results in a signal on the speed/slow lines with a size that measures the difference in arrival times. A similar form of operations appears in connection with brightness differentials on the ζ lines in Fig. 38, where the size of the signal on one ζ line measures a difference in brightness based on two sensors.

In addition to their other uses, I suggest that common differential forms might point to a kind of permanent memory system. I presume that a permanent memory system is embodied in a material medium. See E. R. Kandel, *In Search of Memory* (2006). Such a material embodiment would be a congruent extension of timing device (and Quad Net) principles that are developed from principles of materials science and thermodynamic processes.

One possible approach to memory systems supposes the existence of a “primal activity.” A primal activity holds substantial content and achieves its primacy by being “first” to appear in a situation where other, related activities later appear. In sensory-motor activity, primal activities are those for which our bodies are naturally suited, such as crawling, walking and running. Such primal activities repeat a single form without variation. More complex forms of activity, such as skipping, dancing and accelerated sprinting, are developed from the primal forms by taking the primal form and adding differential spacings and timings.

Hence, I suggest a construction method that starts with a signal specific to a primal activity and that then generates additional signals on the basis of recorded differentials. It is unnecessary to remember all the details of a second memory if they are presumptively “the same” as those in the first memory, except for specific differences. “Balancing unit differentials” can become constituent components in memory re-constructions.

Differentials in Fig. 38 (ζ signals) and Fig. 43.c (speed/slow signals) are stated in a compact code that quantifies an edge-wise comparison between two signals such that a "0" differential means "the signals are the same" (at least in terms of their functions and effects) and a positive magnitude means a power to produce effects, a greater magnitude denoting greater power. These principles parallel those of the Gibbs Free Energy in thermodynamics and apply, e.g., to processes that carry out "matching" and "detecting mis-matches."

The design of Figure 43 develops the method of external following through maintenance of internal silence, as discussed regarding the engineered organisms that "follow the light." (Figures 34 and 35.) Similar to the prior designs, the device assemblies in Fig. 43 are "following the beat" to the extent they maintain a condition close to silence on the speed/slow lines.

The silences in Figure 43 are centerpoint silences, like those in the pulse train version of the engineered organism (Fig. 34). A centerpoint silence has two sides, one on either side of a balance; and activities are different on the two sides. On one side of a silence in Fig. 43 is a signal instructing the pulse bundle generator to speed up; on the other side of such silence is a signal instructing the generator to slow down; and each signal has a distinct line and effect.

4. An Ear for Pythagorean harmonics.

a. the phenomena of Pythagorean harmonics.

A striking feature of musical perception is the fact that two different tones heard together can create a pleasant sensation in the hearer additional to that felt when the two tones are heard separately. Such pleasant sensations are called "harmonics" or "consonances" and are a foundation of music. Another pair of tones heard together might give rise to an unpleasant sensation, called "dissonance," which is experienced as a kind of tension. In a simple song, there is a central tone called the "tonic" and other tones are pleasant or tense according to their consonant or dissonant relationships to the tonic. The song concludes on the tonic in a way that gives pleasure, satisfaction and release from tension.

In a mathematical approach to music, each tone is described by a "pitch" that is usually denoted as a frequency, namely, a certain number of "cycles per second" or Hertz (Hz). A pitch of 440 Hz denotes the sound of a conventionally-tuned violin playing an open A string. A "pitch pipe" is a whistle-like device that produces simple and accurate tones for musicians to tune by. To start, we deal only with tones described by a single "fundamental" pitch.

The ancient sage Pythagoras first discovered that consonance between tones can be identified by simple ratios of whole numbers, such as "3:2." Expressed in the modern language of frequencies: when the frequencies of two tones are in a simple whole number ratio, the pair of tones gives rise to a pleasant sensation or consonance. A musical scale consists of tones that are in certain ratios with respect to one another. Simple ratios identify pleasant pairs and complex ratios identify tense pairs. Pleasure and tension are thus identified with ratios (also known as "pitch relations") and ordered accorded to numbers. Such concepts are part of the body of knowledge known as "harmony."

Without doubt or dispute, the fundamental coupling is 1:1 or unison. The most pleasant ratio is 2:1, or the octave. Then, ratios are found to be pleasant in order according to a scheme: 3:2 (perfect fifth or dominant); 4:3 (perfect fourth or subdominant); 5:4 (major third or mediant). These five notes and relations make up the essence of a scale. In the Ear for Pythagorean Harmonics, the scale is extended to the ratio 6:5, a minor third.

A chief feature of musical experience is that much the "same" pleasure is aroused by any two tones that are in a specific pitch relation, such as 3:2, regardless of the absolute pitch. E.g., two tones of 600 Hz and 400 Hz, heard together, will arouse much the same experience as 660 Hz and 440 Hz, heard together. Accordingly, a musician can "transpose" one set of pitches in one "key" (tonic and subordinate tones) to another set of pitches in another key and yet sustain the musical feelings of pleasure and tension almost exactly.

"An Ear for Pythagorean harmonics," assembled out of timing devices, suggests a basis for these features of perception.

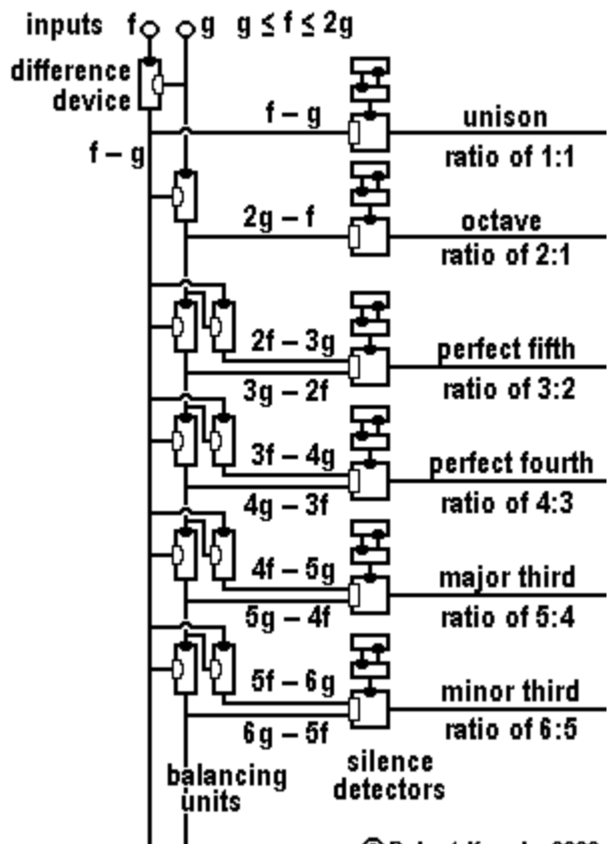
b. design of "an ear for Pythagorean harmonics."

Figure 44 shows the design of "an Ear for Pythagorean harmonics." Two ideal pulse trains are inputs to the Ear, the higher frequency signal denoted by "f" and the lower frequency denoted by "g." Derived (internal) signals have sufficient definition of frequency for purposes described here; key derived frequencies are stated on internal lines in Fig. 44. If desired or needed, irregular signals could be smoothed by a convolution device. (Fig. 22.)

For purposes of this design, the inputs are constrained by the relationship $g \leq f \leq 2g$, spanning an octave on a piano keyboard. If g is middle C, 2g is the C above middle C (" C' ") and f can be any tone between middle C and C'.

The output lines of the Ear are projections from silence detectors that are labeled "unison," "octave," perfect fifth," etc. If the frequencies of the two input signals are in a simple whole-number ratio, e.g., 3:2, the indicated output line carries a positive signal. Most of the time, signals to the silence detector gate keep the gate closed; but signals to the gate are silent for a specific "tuned" harmonic input. The Ear detects Pythagorean harmonics and, with advanced features, the Ear can measure deviations from Pythagorean harmonics – and that is all that the Ear can detect or measure.

Figure 44: An Ear for Pythagorean harmonics



As shown in Fig. 44, the two input signals are processed by the first difference device to generate the signal f–g. The f–g signal goes in two directions: (1) If f = g, f–g=0; the line to top silence detector is silent and a signal appears on the unison line, indicating the equality; (2) the f–g line down the side provides signals for the rest of the Ear.

The second difference device subtracts (f–g) from g. Because $f \leq 2g$, the 2g–f line is always active, except at the limit of the range (2g–f=0) when the line is silent and a signal appears on the "octave" line.

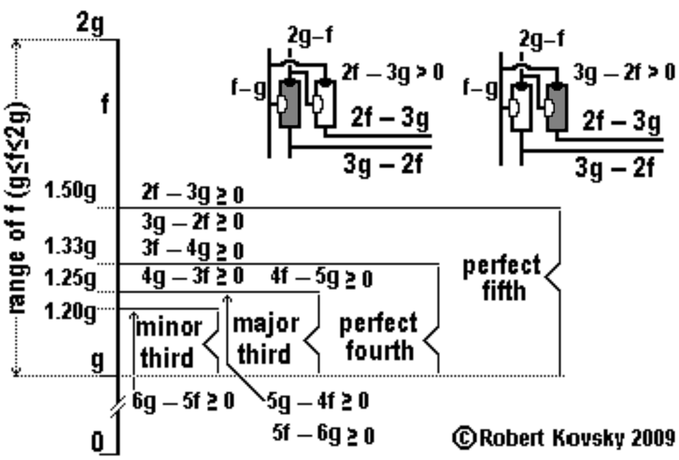
At the level of the perfect fifth, the f–g signal and the 2g–f signal are inputs to a balancing unit. A positive 2f–3g signal will appear on one output line of the balancing unit and a positive 3g–2f signal will appear on the other output line. No more than one line has a positive signal at any moment; and both are silent when 2f–3g = 3g–2f = 0, or f = (3/2)g, resulting in a signal on the "perfect fifth" line.

If $2f–3g \geq 0$, only the f–g signal is active in the last three stages of the Ear. The f–g signal appears on the upper output lines from the last three balancing units onto the respective silence detectors (such signals are not indicated in the Figure). If $3g–2f>0$, the $3g–2f$ signal is balanced against $f–g$. For both control lines to the gate junction in the perfect fourth silence detector to be silent, $(3g–2f) – (f–g) = 0 = (f–g) – (3g–2f)$, or $4g=3f$, the ratio for the perfect fourth interval. Reasoning used in connection with the perfect fifth and fourth intervals is copied for succeeding levels, with a few obvious variations in values of frequencies. As suggested by such copying, there are general principles of operation which apply at all the levels of the Ear.

Looking at the Ear in closer detail, the silence detectors are only of secondary importance. Of chief importance are: (1) signals on the lines from the difference devices to the silence detectors and (2) the organization of the spectrum of frequencies between g and 2g, as shown in Figure 45.

The graphical part of Figure 45 shows the frequency spectrum of the Ear, along with specific frequencies and intervals. The schematic part of Figure 45 shows how device operations change as the frequency shifts from $2f–3g>0$ to $3g–2f>0$, around $f=1.50g$. When $2f–3g>0$, one device in the balancing unit is silent (darkened device) and the other is generating a signal with frequency $2f–3g$ (active device); when $3g–2f>0$, the operational roles are reversed. Similar reversals occur at the other boundaries – at the frequencies of the Pythagorean harmonics.

Figure 45: frequency boundaries and intervals in an operating Ear for Pythagorean harmonics



Consider a process – the "f reduction process" – where f changes continuously from an initial value of $f=2g$ to a final value of $f=g$, spanning its range in the course of the process.

When $f=2g$, $(n)f–(n+1)g = (n–1)g$, as to each balancing unit in the Ear, the upper line is active and the lower line is silent, with corresponding active and silent difference devices. E.g., if $f=2g$, then $2f–3g=g>0$, the $2f–3g$ line and its difference device are active and the $3g–2f$ line and its difference device are silent.

The overall situation is, at first, unchanging as the frequency is lowered from $f=2g$ – until the frequency passes through the $f=1.5g$ level. Then the difference devices at that level switch operational roles as shown in Figure 45. Difference devices at lower levels stay in the $f=2g$ operational roles as f passes below the $f=1.5g$ level, at least until it reaches the $f=1.33g$ level (the perfect fourth interval), when switching takes place at that level in a fashion similar to that shown in Fig. 45.

The frequency spectrum of the Ear is thus partitioned into sub-ranges where the Pythagorean harmonics mark the boundaries. Each sub-range is a distinct phase and corresponds to a distinct operating patterns of difference devices; difference devices switch on and off as the system passes through a phase boundary.

Because of the smoothness and continuity of the “g period reduction process” in difference devices, discussed in point E.1, transitions are smooth and continuous at each level of the Ear.

In partitioning the frequency spectrum, the design of the Ear develops themes introduced with the frequency analyzer (Figures 10 and 11). In the frequency analyzer, a single root frequency and a step value leads to a series of equal steps – a ladder structure – organized through addition. In the Ear, in contrast, the spectrum is generated by a pair of frequencies and levels are based on ratios. In the more complex operations possible with the Ear, both f and g can vary, additional voices can be added and intervals can be organized into larger-scale forms. As suggested by the rich diversity of musical harmonic material, the structures of the Ear promise much more development than a ladder structure generated through addition.

Of chief importance in the design of the Ear is further development of “the method of external following through maintenance of internal balanced silence” discussed in connection with Figures 35, 36 and 43, in connection “following a light” and “following the beat.” Here, it is a Pythagorean harmonic that is being followed.

To illustrate the nature of “following the harmonic,” suppose that an accompanist plays a tone on the flute while an “engineered singer” vocalizes a perfect fifth above the flute tone. The engineered singer has an “internal harmonic generator” that is like the “internal beat generator” discussed in connection with Figure 43 and the engineered singer has an Ear for Pythagorean harmonics operating at the perfect fifth level. If signal g is the tone of the flute perceived by the singer and signal f is the tone produced by the singer, the production of the tone $f=(3/2)g$ can be controlled through operations that resemble those of “following the beat.” At the centerpoint, silent inputs open the gate of the silence detector for the perfect fifth and the silence detector produces a signal indicating that fact. If there is a fluctuation on the part of the internal harmonic generator and the produced tone goes “flat,” signals appear on the $3g–2f>0$ line, which leads to the equivalent of “tightening” for higher tone production. If the produced tone is “sharp,” signals appear on the $2f–3g>0$ line and there is “relaxation” for lower tone production. See Figure 43, showing a similar arrangement for following the beat.

Thus, in the context of device operations, I suggest that the Pythagorean harmonics take on additional and new roles. They maintain their roles as important static ratios but they also gain a dynamic character. Each silence, each Pythagorean harmonic, marks a frequency ratio that can be maintained as a standard for purposes of stabilization and control, with an efficient means of adjustment that involves increasing or decreasing an appropriate variable of a control signal.

What was a single “centerpoint silence” in the “following the light” engineered organism and the “following the beat” design has become a spectrum of silences in the Ear for Pythagorean harmonics. A spectrum of silences suggests multiple possible paths for tonal motion. System principles appear to support a next stage of development: a timing device assembly that combines “following the beat” and “following a harmonic” and that can “follow a tune.”

c. Human experience is congruent with operating principles of the Ear.

I suggest that operating principles of the Ear for Pythagorean harmonics apply to human auditory experience.

First, I suggest that a human violinist tunes her instrument through use of the perfect fifth interval in much the same way as the "engineered singer," discussed in the preceding subsection adjusts its pitch. Suppose that a concert-hall violinist has first tuned her A string to the tone played by the oboist; then, she tunes the D string (the string below the A string) by playing or plucking both open A and open D strings while turning the "tuning peg" for the D-string to and fro and thus adjusting the interval between the open D string and the open A string, seeking to make that interval into a perfect fifth. If the A-string is in tune and the perfect fifth is sounding, the D-string is also in tune.

I suggest that tuning by human ear is possible because the human ear detects a perfect fifth in a fashion similar to that of the timing device Ear. It is the universality and clarity of the perfect fifth relationship that makes this tuning method possible. A typical violinist cannot tune her violin by ear to the interval of an "equal-tempered fifth" that is different from a perfect fifth and that is used to tune a piano; rather, the violinist needs a piano or tuning aid to match that interval.

Looking more closely at the Ear for Pythagorean harmonics, its chief operating components are difference devices, beginning with the difference device that produces a "difference signal" (f – g) from two input signals. Difference signals appear in multiple ways in human experience.

A person hears such a difference signal when the frequencies of two inputs signals are close to each other, e.g., within a few Hz; and what is heard sounds like a slow beat. The frequency of the difference signal is called a "beat frequency."

Another kind of difference signal, known as "binaural beats," is generated if one input signal is heard solely by one ear and another, different input signal is heard solely by the other ear. Such "beat tones" having a difference frequency (f–g) are clearly the product of neuronal activity. Various websites offer discussions and demonstrations of binaural beats.

As another example, musical analysis divides the rich and complex sound of a musical instrument into a "fundamental tone" (the tone sounding at the frequency shown on a musical score) and a set of "overtones." Each overtone is at a frequency that is a multiple of the fundamental tone; and each instrument produces a characteristic set of overtones, in different proportions depending on the instrument. A flute produces a few overtones that have low multipliers while a trumpet produces many overtones that have high multipliers.

When two fundamental tones are played together and they are also overtones of a third fundamental tone, a musician will hear that third fundamental tone, even though there is no such sound in the air. It is called the "missing fundamental." For example., if open strings A and E are played together, a perfect fifth apart, the musician will also hear an A tone an octave lower, call it "a." As a further example, when a first tone is heard with a second tone that is a perfect fourth above the first; the musician will hear a tone that is two octaves lower than the second, higher tone.   Hence if E and A' (an octave above A) are heard together, the musician will also hear an a.

The Ear for Pythagorean harmonics provides an account for missing fundamentals. The (f–g) difference tone corresponds to the frequency of a=220 Hz. Given frequencies A=440 Hz (first overtone of a), E=660 Hz (second overtone of a) and A'=880 Hz (third overtone of a), the difference tone for a can be either 660-440 or 880-660.

"Thus, if tones of 800, 1200, and 1600 Hz occurred together, they would create an illusory difference tone of 400 Hz. This tone that is heard, but is not actually present in the stimulus, is often referred to as the missing fundamental." Janet D. Larsen, Klaus Fritsch, "A Valid Demonstration of the Missing Fundamental Illusion," available online.

What these phenomena show is that, in addition to experiences that are directly based in environmental stimuli, such as input signals f and g, there are also experiences that are generated internally in a derivative way. The difference signal (f–g) is clearly a source for derived experiences. A derived experience is a full and authentic experience but it stands secondary with respect to environmental stimuli, without which it does not exist.

The Ear for Pythagorean harmonics generates an array of derived signals. The simplicity of the design and the congruence between its (f–g) difference signal and signals in brains suggests the presence of derived experience based on further derived signals, including the 2g–f (the octave) and the balanced pair of signals (3g–2f and 2f–3g) that define the perfect fifth.   I suggest that experience of a balanced pair of signals, e.g., those defining the perfect fifth, is experience of centerpoint balancing through muscular effort, e.g., experience of a singer reaching for a high note or that of a French horn playing a rising call during a concert performance. It is like a trapeze artist jumping through the air and seizing hold of a flying swing. The audience pays to get the pleasure of the achievement without having to undertake any effort or risk.

A final area of congruence between the Ear and human experience is shown by "harmonic resemblances" that arise from the frequency spectrum and boundaries of Figure 45. As shown in Figure 46, important resemblances appear when an octave that has been split into a fifth and a fourth (Fig. 46.a) is viewed in juxtaposition with a fifth that has been split into a major third and a minor third (Fig. 46.b). Because the Ear is based on ratios of frequencies rather than an absolute frequency, the fundamental tone g=60 Hz is used for arithmetical convenience. Other intervals and frequencies follow: the octave is at 120 Hz, the fifth is at 90 Hz, the fourth is at 80 Hz, the major third is at 75 Hz and the minor third is at 72 Hz.

I suggest that the two structures of intervals, organized within the octave and within the fifth respectively, show resemblances in musicians' experience and in the graphical relations of Figure 46. Some resemblances connect phenomena in ways that cannot be satisfactorily stated in words but that can be heard when played on a keyboard.

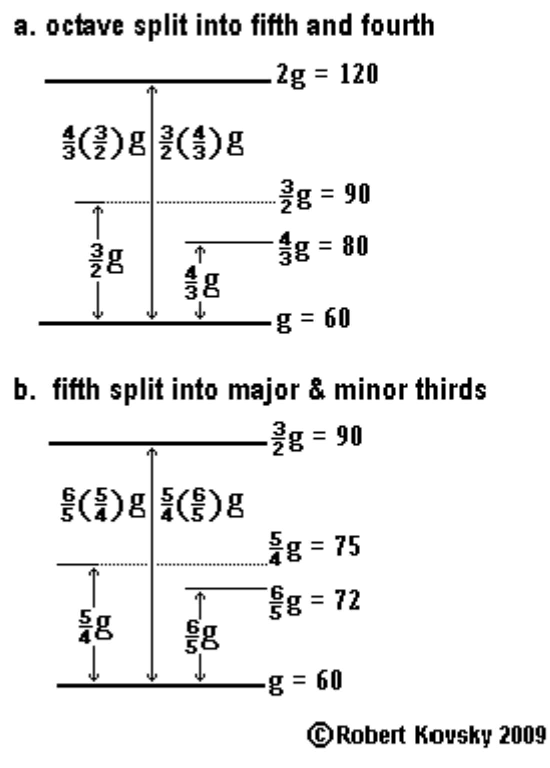
An octave split into a lower fifth and an upper fourth was the typical harmonic foundation and final sonority of a medieval musical work. Similarly, a fifth split into a lower major third and a minor upper third – a major triad – is the typical harmonic foundation and final sonority of a work written in the "modern era," i.e., after 1600. For example, compare C-G-C' with C-E-G.

The construction theme for both sets of intervals and relations is that the two smaller intervals nest within the larger interval. Moreover, the intervals and relations in the split fifth nest within the intervals and relations in the split octave, providing a richer sonority. This is a case of "self-similarity" because one part of the split octave, the fifth that can be split, is similar to the split octave as a whole.

The intervals and relations also allow for a lower fourth and upper fifth within the split octave; and, likewise, for a lower minor third and upper major third within the split fifth. In both cases, the more stable sonority occurs when the greater interval is in the lower position and the sense of resolution heard when the intervals shift to change the greater interval from top to the bottom is similar in the two cases.

The frequencies of the three notes in the split octave are in the ratios 2:3:4 while those in the split fifth are in the ratios 4:5:6. Such simple ratios are characteristic of the Ear for Pythagorean harmonics.

Figure 46: harmonic resemblances



(For background, please see Schulter, Margo, "Were there triads in medieval music?" at http://www.medieval.org/emfaq/harmony/triad.html and, more generally, Schrade, Leo, *Monteverdi: Creator of Modern Music,* 1950.)

The Ear for Pythagorean harmonics generates the core of a musical scale that is called a "just" or "natural" scale and that is based on a principle of repeated subtraction. Other scales have been based on a principle of repeated multiplication. For example, the scales used in medieval music were based on repeated multiplication by a factor of 3/2 (the "perfect fifth" ratio) and on a principle of equivalence between tones separated by an octave or an integral number of octaves (c=C=C'=C").

Many musicians hold that a natural scale has superior purity and stability of tonal relations. Scales constructed according to a multiplication principle, on the other hand, allow for easier and more distant modulations between keys and they provide superior means for organizing voices in different registers, e.g., for choral performances in the Church.

Scales built according to the multiplication principle emphasized the fifth and fourth; they were broad in reach, with theorists claiming to state universal rules but also confining the art of composition to a narrow liturgical specialty. In contrast, scales built according to the subtraction principle emphasize the major and minor thirds; they have a short reach and start with only a few moves; but the moves are congruent with folk music and are capable of "expressing even the most delicate and secret emotions of the soul. ... We find proof of this in contemporary chronicles which point out as fact worthy of record that – in 1607 – in Monteverdi's opera *Arianne*, the forlorn heroine's lament caused listeners to melt in tears." (Dorian, Frederick, *The History of Music in Performance* (Norton 1966) at 49, quoting Curt Sachs.)

One lesson from this brief history is that neither a pure multiplication principle nor a pure subtraction principle can generate a fully satisfactory and comprehensive harmonic system.

Scales used in medieval music that were constructed according to a pure multiplication principle had rougher-sounding thirds than those used in the modern era. Changes that started in the fifteenth century led to adjustments in the size of the intervals for the major and minor thirds, bringing them closer to those of the natural scale and making them more pleasing to the ear. Gioseffo Zarlino (1517 – 1590), among the activists who led music out of the Church and into courtly and theatrical performances, taught that singers should use "natural" intervals, although it is not clear that this teaching was practical. Musical scales went through a period of development that culminated in the acceptance of the "equal-tempered" scale during the eighteenth century, a scale which incorporates many compromises.

(On scale changes, see Schulter, M, "Pythagorean Tuning and Medieval Polyphony," § 5.3, http://www.medieval.org/emfaq/harmony/pyth5.html#3; on Zarlino and natural intervals, see Bettens, O, "Renaissance 'Just Intonation' – Attainable Standard or Utopian Dream?" http://www.medieval.org/emfaq/zarlino/article1.html *et. seq*.)

Developments in scales were thus part of the development of emotionally expressive music. Music became more expressive when scales were adjusted to conform more closely to the scale that is congruent with the Ear for Pythagorean harmonics. These adjustments support the conclusion that a "natural scale" rightly bears that name because its intervals conform to those generated by neuronal processes. I suggest, therefore, that congruence between principles of the Ear and facts of human auditory experience is shown by the history of musical development.

F. Conclusion: The Leading Power of Silence

Review of the foregoing timing device designs suggests principles for future development.

The first principle, previewed in point A.2, is that action precedes sensation and that the function of sensation is to select actions and to control switching between actions. If an organism has only one form of action, sensation is non-functional – the same action will be performed whatever the sensation. If an organism has exactly two forms of action and a capacity to switch between them, the function of sensation is solely to trigger a change from one form of action to the other. The engineered organism shown in Figure 34 (pulse train version) comes close to this extremely limited functionality – it has three forms of action with variable distributions in time.

A comparably simple situation from the perspective of human experience is that of a motorist waiting for a traffic light at a typical two-street intersection, who will move his right foot from the brake pedal to the accelerator when the traffic light changes from red to green. The change in the traffic light is all that the motorist has to see to trigger his movement. (Of course, better driving practice is be ready for any kind of stimulus.)

As shown by the development of the engineered organisms from Figure 34 to Fig. 35, forms of action grow more varied and interwoven as a result of development; and corresponding forms of sensation take on a greater number of possibilities. Possibilities can be organized through specific combinations of sensation and action that enable the person to control and coordinate action effectively, e.g., keystrokes on a computer or piano keyboard. The invention of new forms of action is the most powerful generator of development; examples include human speech and all kinds of technology. New forms of action for timing device systems might include differential control over rates of a set of chemical reactions or biological processes.

With respect to sensation – action's subordinate conjugal partner – designs herein view sensation at a rudimentary level of development, when sensations are no more than "signs" that match up with different triggering possibilities for action. At a certain point in development, sensation will progress beyond signs and develop into "symbols" and "imagery." Present timing device designs are too primitive for symbols or imagery, e.g., imagery or symbols constituting knowledge of a spatial terrain through which the organism is moving. "Doing" comes before "knowing" in brain models built from timing devices.

The second principle is "family and resemblances" or, simply the principle of "resemblances." Operationally, timing device systems (and the more general Quad Net Model) generate activity patterns that are related by resemblances. The psychological counterpart states that experiences come in the same form. A developmental goal is to relate families of activity patterns in device models of brains to families of experiences generated by brains. Details of the relations are to be expressed through resemblances. Quad Net device models generate families of activity patterns and select among them (principle of Shimmering Sensitivity).

Psychological resemblances (that a person experiences) can range from those that relate identical twins (one-to-one) to those that relate polar opposites (governed by a principle of mutual exclusion). "Families" includes tunes, food tastes and colors. Resemblances is a principle that unites all domains of human experience and that extends through multiple levels of complexity in each domain, a detail sometimes bearing resemblances to the organic whole, e.g., an era that has the character of its ruling politician.

The primal case – or point of origin – of the principle of resemblances is a biological family of persons (originally a clan) related by birth and marriage who share resemblances of bodily parts, characteristics of personality and personal history. More refined examples of resemblances include simplified sensory experiences like pairs of musical tones investigated by the Ear for Pythagorean harmonics and complex constructs like reviews of opera performances. Resemblances make up the content of biological taxonomy, the periodic table of elements, judicial interpretations of legal precedents and biblical exegesis. The principle of resemblances applies, of course, to timing devices and further discussion here is limited to that application.

In timing device systems, pulse streams come in the large families of pulse trains and pulse bundles; various pulse patterns cluster around the ideals. Resemblances between pulse patterns are often stated in terms of comparable frequencies. (Figures 6, 11, 15, 35, 44.) Differentials measure the differences between signals that otherwise resemble each other. (Figures 34-36, 38-39, 42-43). Timing devices themselves resemble one other through common features, e.g., the 2 signals-into-1 arrangement shared by distinct devices (Figures 8, 12, 16 and 30). Different forms of the "the method of external following through maintenance of internal balanced silence" appear in various timing device designs (Figures 34, 35, 43, 45). All of these show the principle of resemblances implicitly. Explicit harmonic resemblances (Fig. 46) make up another topic.

Device designs reveal more resemblances. Three subject matters investigated through timing device designs – namely, music, mathematics and muscular movement – are inter-related through dance (music and muscular movement), the mathematics of music and the mathematics of gaits of animal locomotion, such as walk, trot, gallop (see, e.g., work by Ian Stewart and Martin Golubitsky).

I suggest that the Ear for Pythagorean harmonics, discussed in connection with music and mathematics, also has potential for application in the domain of muscular movement. That is, I suggest that a device like the Ear can control relations between muscular movements like the Ear controls relations between tones. In the domain of muscular movement, a device based on principles of the Ear would function like an automobile gearbox. A first level of activity can be coordinated with a second level of activity through one of several specific ratios and the specific ratio of coordination is selected to best accomplish a specific purpose.

I suggest that, using a device based on the Ear in operations of muscular systems and in a fashion similar to that of an automobile gearshift, intensity of activity can jump from one level where activity is stabilized through centerpoint balancing around a silence to another, quite different level where activity is again stabilized through centerpoint balancing around a silence. Such a jump, phasic in nature, would be quicker than a series of incremental changes that must be stabilized at each step. It is like a singer "jumping" to an octave or perfect fifth above a prior tone. Such a jump is part of an alternative answer to questions of quick switching between behaviors, discussed in the Introduction, point A.3.

The third principle for the development of timing device systems – as well as for the more general Quad Net Model – is the principle of silence. The principle of silence states that each production of pulses is, at the same time, a production of silences. Increasingly complex signals are described in terms of pulse patterns but they are also described in terms of structures of silences -- and the structures of silences may provide a more useful description.

Each of the primal timing intervals is a silence. The responding period δ is a period of silence between the instant the timing device is stimulated by the arrival of a pulse and the instant the timing device responds by discharging another pulse. It is a dynamic, pregnant silence that occurs while action is impending but it is silence nonetheless. The refractory period β, on the other hand, is a period of inert silence.

Readiness is also a condition of silence. If there is a defined readiness period, γ, there is a defined period of silence, ready and waiting for a stimulus, different from both the silence of the responding period, when action is pregnant and impending, and that of the refractory period, when the device is inert. The three fundamental silences – β, γ and δ – are building blocks for simple timing device signals. The principle of resemblances suggests that these characteristics can be developed and organized in large-scale constructions.

As complexity develops, so do silences. The rousal period ξ (Figure 8) is "silence with a vengeance," since the possibility of a pulse will be lost if the silence is not broken by the arrival of a second input pulse before the expiration of ξ. The frequency detector and frequency analyzer (Figures 9 and 10) detect particular periods between pulses, or particular silences.

Blocs of silence" interwoven with "blocs of pulses" are introduced with the gate timing devices (Figures 12 and 14) and regularized with pulse bundles (figure 21). "Big silences" separating blocs of pulses and "small silences" within blocs of pulses are distinguished and treated differently in the τ_{MAX} – modified streaming device (Figure 26). In the difference device, yet another kind of silence is introduced, a "hole" (point E.1). There is sustained development of "the method of external following through maintenance of internal balanced silence." (Figures 34, 35, 43, 45) Silence occurs when two memories match. (Fig. 42.)

Uses of silence in the action system of timing devices parallel uses of zero in the static conceptual system of mathematics. An equation stands as a balanced construction in a static sense: $E=mc^2$ is equivalent to $E–mc^2 = 0$. In mathematical physics, a constant state G is symbolized as $dG/dT = 0$. Generalized formulations of mechanics (e.g., the Lagrangian formulation) focus on points of stabilization occurring when $dF/dq = 0$ (and $d^2F/dq^2>0$). Conservation of a quantity is expressed by a "0" statement, e.g., $\Delta\Sigma\mathbf{p}=0$ expresses conservation of momentum.

Stable and balanced streams of pulses in the timing device system approximate such 0 states. (Figures 19, 30, 38 and 44.) The stability of balanced streams is maintained through dynamical balancing around a centerpoint silence. Timing device operations can function like mathematical operations, e.g., addition (Fig. 18 *et. seq.*), subtraction (Fig. 30 *et. seq.*), multiplication by a real number (Fig. 22) and convolution (point D.3).

Notwithstanding operational parallels, I suggest that mathematics and timing device systems are distinct species of mental constructions. Obviously, timing device systems, at least as presently conceived, occupy a low level of concreteness in contrast to high levels of abstraction inhabited by mathematics. On the other hand, as has been suggested herein, I hold to a position that mathematics and mathematical physics are also limited in their capacities to describe reality and do not reach the facts of phase changes, such as phase changes that take place in our brains – or in assemblies of Quad Net devices.

(My position is supported by critical examination of physicists' claims that mathematical physics describes and "explains" the phase change from water vapor to ice crystals that results in snowflakes. Please see http://www.testimony-of-freedom.com/snowflakes.html)

I also suggest that timing device systems and computers are distinct species of device constructions. Topics for further investigation are (1) to extent to which a timing device system can emulate a computer, e.g., a Universal Turing Machine; and (2) the extent to which computers can emulate activities of timing device systems. As to the latter question, computers would likely emulate timing device operations that are stabilized, that is, where stabilized streams of pulses have operational parallels to mathematical states. Emulation would be less successful, I suggest, were computers to try to emulate phase changes in timing device systems, especially phase changes in response to happenstance environmental stimuli. I suggest that similar phase changes occur during muscular action controlled by biological brains.

Activities and silences in muscular systems are dynamically balanced rather than statically stabilized. Something like silence in muscular systems is maintained through agonist-antagonist muscle pairs, like the biceps in the arm that close (flex) the elbow joint and the triceps that open up (extend) the elbow joint. When the arm is not being used but is being held in readiness, both biceps and triceps are continuously stimulated but the stimulations are in such a proportion that the arm does not move. In an excited condition of readiness, there may be a continuous to-and-fro movement that is usually on a fine, imperceptible scale but that may become apparent with age or loss of muscular control. Whether the arm is quivering in readiness or apparently immobile, impulses and movements of the arm are followed by contrary impulses and movements that balance what has previously occurred.

As a result of the continuous stimulation to maintain the dynamic balancing, muscles are said to have a certain "tone" or "tonus" and the meanings of the quoted terms have close resemblances to those of "tonic" in music. "Tonus" or "tonic" means that there is a foundational signal that identifies a foundational experience. Content is a signal that has greater intense than the foundational signal and that is specific to the domain, e.g., muscular effort or musical tone. Any content is momentarily stable but moveable, e.g., by exerting more muscular effort or by singing or playing a higher note; and movements may be made in multiple directions or multiple ways.

I suggest that finely controlled and variable movement in muscular systems is possible because of centerpoint balancing that can occur at multiple levels of activity controlled by small critical deviations from the balance. Small critical deviations are called differentials in connection with Figures 35, 36, 38, 39 and 43. In addition to differential control around a foundational tonus or tonic, a muscular system should have the capacity to jump between levels of activity and to switch between them.

I suggest that control will be imposed through constructions of "cycles within a cycle" or "nested cycles" Such control occurs in parallel with construction of "silences within a silence" or "nested silences."

The primal example of nested cycles is pulse bundles where the organizing period τ_ψ is much longer than the signal period τ_φ. (Fig. 21.a.) The organization period for a pulse bundle generator is defined by a single pulse between long periods of silence. (Fig. 29.) In a higher-level nesting with "bundles of pulse bundles," (Fig. 21.b), the organizational periods, $\tau_{\omega,}$ are longer still and the silences are also longer. "Deliberation," during which memories of past events are coordinated with possible future events, might require consideration of various coordination patterns and lead to even longer periods and slower processes.

In sum, development in timing device designs shows progressively more complex use of silences, in parallel with more complex pulse patterns. The capacity to control silences is equivalent to the capacity to control pulse patterns.

In an organism engaging in purposeful and efficient action, actions come out of silence. A golfer commencing a stroke requires the same silence as a symphony orchestra commencing to play in a concert hall and a mathematician commencing a proof. Silences are imposed so that a person can control and coordinate multiple sub-systems. Purposeful and efficient action is maintained by means of internal silences. When internal silences are cycling smoothly in coordination with and within one another, operations are harmonious. Hence, I suggest that further developments in the design of brain models built from timing devices might grow out of a foundation of harmonious silences, ratios and resemblances, commencing with those operating in an Ear for Pythagorean harmonics.