Summary.

Timing devices are proposed electronic components that can be assembled into networks. An individual timing device embodies essential functions of a neuron and a network of timing devices acts like the nervous system of an animal and operates an ***engineered organism*** (Figure 27). Some timing devices in the engineered organism drive muscle-like fibers while other timing devices are sensitive to the environment and act as sensors. Sensors produce signals that control muscle-like twitches so as to direct the engineered organism with respect to a the source of stimulation, e.g., towards a light or a particular food-like molecule.

Signals in a network of timing devices are made up of distinct, uniform ***pulses***, resembling "spikes" or action potentials in neurons. In the simplest case (Figure 1), one pulse is an input to a timing device and ***triggers a response process*** within the timing device. The response process is governed by ***timing intervals*** and produces one pulse as output. A pulse produced as output by one timing device typically acts as an input to another timing device.

More complex timing devices have multiple inputs and multiple outputs. Activity of a complex timing device is governed, at a first level, by a ***trigger rule,*** where one or two input pulses trigger the response process, which is governed by timing intervals. At a second level, input pulses modify timing intervals according to a ***modulation rule*** (Figure 15).

A network of timing devices is made up of smaller ***assemblies***; and a ***pulse train*** is made up of a sequence of pulses. An assembly performs a distinct function with respect to a pulse train. E.g., certain "pulse period detectors" (Figures 9 through 12) produce output only when input pulses in a train are separated by a period of time of a specific duration, or nearly so; and the assembly acts like a bandpass filter in an electronic circuit.

The presentation concludes with examples of assemblies (Figures 28 through 33) where behavior of the network changes discontinuously in overall ways in response to small changes in the timing of sensory stimuli. I suggest that such behavior cannot be emulated by a computer, where the fundamental time step (a clock tick) is fixed. Emulation would seem to require an indefinitely large or "infinite" number of infinitesimal steps to represent large-scale changes in operations caused by unpredictable sensory stimuli. It appears that, although behavior of such a network of timing devices is determinate, it is beyond the reach of computation.

Table of Contents

1. A simple timing device

A simple timing device is stimulated by an input pulse and responds with an output pulse after a certain period of time. Such periods of time constitute the chief subject matter of the presentation. Generally, activities of timing devices are stated and developed in terms of ***clocks, periods of time, pulses, processes***, and ***conditions***. There is a ***realtime clock*** that tracks time globally in terms of a time variable t, what we think of as ordinary time. The global t=0 is set for convenience. A ***period of time*** is a duration measured by the realtime clock.

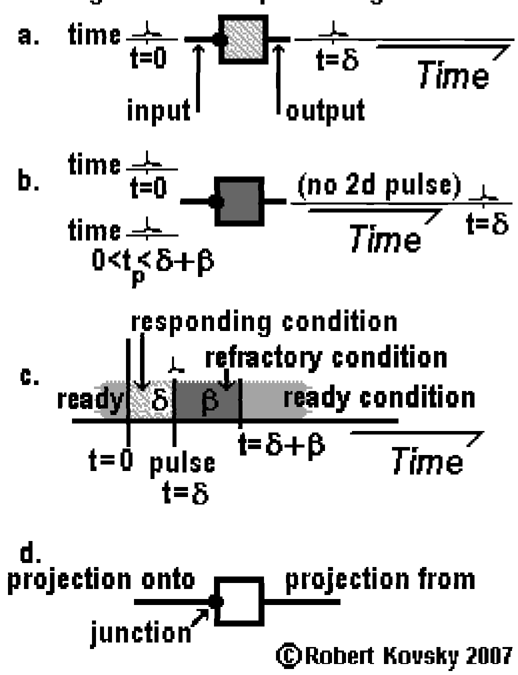
A ***pulse*** is a distinct unit signal that is convenient to produce and detect. The duration of a pulse is much shorter than that of all other periods of time. In this presentation, a pulse occurs in an instant (a duration that approaches 0) but nonzero durations would not alter functionality or the argument. Pulses are ***uniform***, that is, so close to identical that variations are inconsequential.

The simple timing device incorporates the ***response process*** shown in Figures 1.a through 1.c. The response process is a sequence of ***conditions***. A ***response clock*** is an integral component of each timing device and controls changes from one condition to the next. Each timing device has an independent response clock that is initially stopped at its own 0, like a stopwatch; and the response clock of a timing device returns to such initial stopped state at the end of the process.

In Figure 1.a, an input pulse is incident onto the timing device at global t=0. The input pulse has been produced by another timing device or by a researcher. The input pulse triggers the response process and starts the response clock. After a period of time – the ***response period***, denoted by δ – the timing device produces a single output pulse. Input and output pulses are carried by conductors, i.e., wires; the respective wires are also called input and output.

After the timing device produces the output pulse, it is non-responsive and cannot be stimulated by a new input pulse for an additional period of time, the ***refractory period***, denoted by β. As shown in Figure 1.b, if an input pulse starts the response clock of a timing device at time t=0, the timing device will be non-responsive to a second pulse both during the time it is responding to the first pulse (duration δ) and also during the additional refractory period (duration β), for a total of δ+β. In other words, if two input pulses arrive, the first at t=0 and the second at $t=t_p$, the timing device will respond to the first pulse by producing an output pulse at t=δ; but ***no*** second output pulse will be produced if the second input pulse arrives before the end of the refractory period, i.e. if $t_p<\delta+\beta$; see Figure 1.b.

Figure 1: a simple timing device



After the refractory period is over, the timing device becomes ***ready*** to be triggered by a new input pulse: the response process terminates and the response clock of the timing device is stopped and reset to its own 0; it can then be triggered again the same as before. The succession of periods and conditions is shown in Figure 1.c.

In Figure 1.a and 1.b, an additional requirement is that the timing device is ready at just before t=0, as shown in Figure 1.c. There are three ***conditions*** that characterize this simple timing device, the ***responding condition***, the ***refractory condition*** and the ***ready condition***. In the simple timing device, the responding condition and refractory condition are each confined to fixed periods; that is, each condition has a specific duration. Formally, each period of time is an open interval of time – "open" means that the period does not include the endpoints. Figure 1.c shows a cycle of conditions in the timing device.

The responding period and the refractory period are ***timing intervals*** that control the activities of the simple timing device.

Conceptually, each timing device has one or more knobs on it, each knob setting the duration of a specific timing interval. In more complex timing devices, such durations may be subject to modifications as a consequence of modulation rules discussed in section 6.

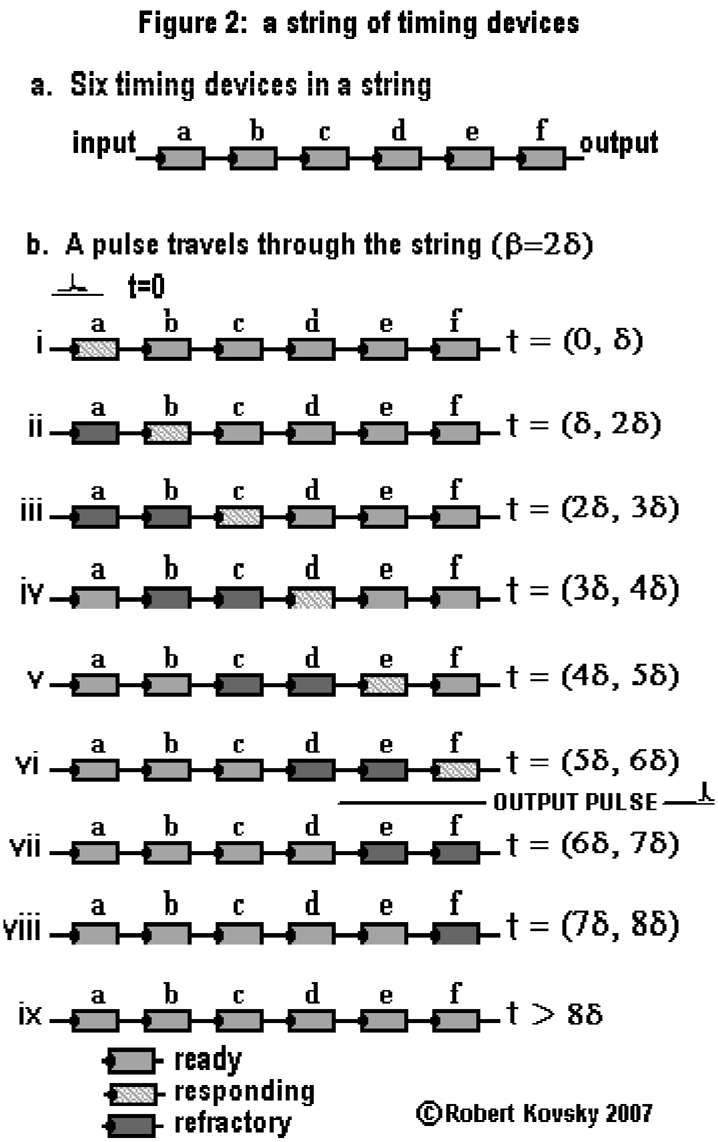
A pulse is idealized as an instantaneous event that occurs between open intervals, e.g., between $(0, \delta)$ and $(\delta,\delta+\beta)$ in Figure 1.c. There are three transitions between conditions, a first occurring on arrival of the input pulse at t=0 (ready condition changes to responding condition), a second on pulse production at $t=\delta$ (responding condition changes to refractory condition) and the third at $t=(\delta +\beta)$ when, at the end of the refractory period, the timing device again becomes ready. Each transition is idealized as an instantaneous event and is marked by a vertical line in Figure 1.c. As a practical matter, the response period and refractory period cover up deviations from ideals of instantaneous pulses.

Figure 1.d identifies the projections, which are physical features of timing devices, and the input and output signals they carry. An output signal is carried via a ***projection from*** the timing device that produces pulses. Typically, a "projection from" one timing device terminates by connecting to a second timing device and it then becomes a ***projection onto*** that second timing device by means of which an input signal can be delivered. Alternatively, a researcher sends an input pulse to the timing device through a projection onto. The termination "onto" a timing device is through a ***junction***. A junction is an active point of contact between a projection and a timing devices. A junction is denoted by a dot in the Figures. The junctions are like synapses in neurons and are the places where interactions are specified, e.g., where timing intervals are modified. Other than at a junction, a projection is a "passive" carrier of pulses, like an electrical wire.

2. A string of simple timing devices

To connect or assemble two timing devices, a projection from a first timing device is extended and terminates, through a junction, as a projection onto a second timing device.

Figure 2.a shows six simple timing devices assembled to make up a string. The timing devices have a common response period δ. The common refractory period, β, is set at β=2δ.



The only input to the assembly is provided by the projection onto timing device a. The only output is the projection from timing device f. In Figure 2.a, all six timing devices are in the ready condition. Each can be triggered but an input from outside is needed to initiate action. Collectively, the condition of the assembly is ***ready and waiting***.

In Figure 2.b activity starts with an input pulse onto timing device a at time t=0 defined by the realtime clock. Figure 2.b.i shows conditions that are present from just after t=0, when timing device a begins responding, until just before t=δ. The period of time is denoted (0, δ). As time measured by the realtime clock passes from t<δ to t>δ, timing device a produces a pulse and changes to the refractory condition. The pulse produced by timing device a becomes an input pulse to timing device b that triggers the response process in timing device b, starting its response clock as its condition changes to "responding."

Figure 2.b.ii. shows the conditions during the period of time from δ to 2δ. As time passes from t<2δ to t>2δ, timing device b produces a pulse and changes to the refractory condition. The pulse produced by timing device b triggers the response process in timing device c and starts its clock, leading to the conditions in Figure 2.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 realtime by δ.   Timing devices in the string produce pulses successively in both realtime and in space. As a consequence, a ***pulse wave*** passes through the string.   The pulse wave shown in Figure 2.b is governed by a single constraint: δ. In effect, δ is the "clock tick" that marks changes in conditions in the string. The pulse wave passes through the string and emerges as an output pulse at t=6δ, shown in Figure 2.b. After t=8δ, the string is again ready and waiting.

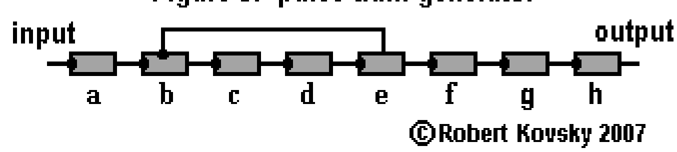
Associated with the pulse wave are (1) a ***responding wave*** identified by the responding condition in timing devices prior to the discharge of a pulse and (2) a ***refractory wave*** identified by the refractory condition in timing devices after the discharge of a pulse. The responding wave, the pulse wave and the refractory wave together make up an ***activity wave*** that passes through the assembly. Within the activity wave, timing devices are all involved in response processes and have running response clocks; but none are so involved or so running outside the activity wave.

Here, the refractory wave is defined by the constraint β=2δ. This constraint is convenient for purposes of illustration because two transitions occur simultaneously, namely, the transition from the refractory condition to the ready condition in one timing device and the transition from responding condition to the refractory condition in another timing device. Hence, the number of images is reduced by half.   Generally, there need not be any particular ratio between δ and β. The effects of the constraint β=2δ depend on the nature of the assembly. In the assembly in Figure 2, there is no change in the pulse wave or the responding wave as β varies from 0 to some indefinitely large number.   As to function, variations in β are ***inconsequential*** in this assembly. The next assembly behaves differently.

3. Pulse train generator

The pulse train generator shown in Figure 3 is identical to the string of timing devices shown in Figure 2, except that there is a new, additional projection from timing device e onto timing device b. The timing devices in Figure 3 are all governed by common timing intervals, δ and β.

Figure 3: pulse train generator



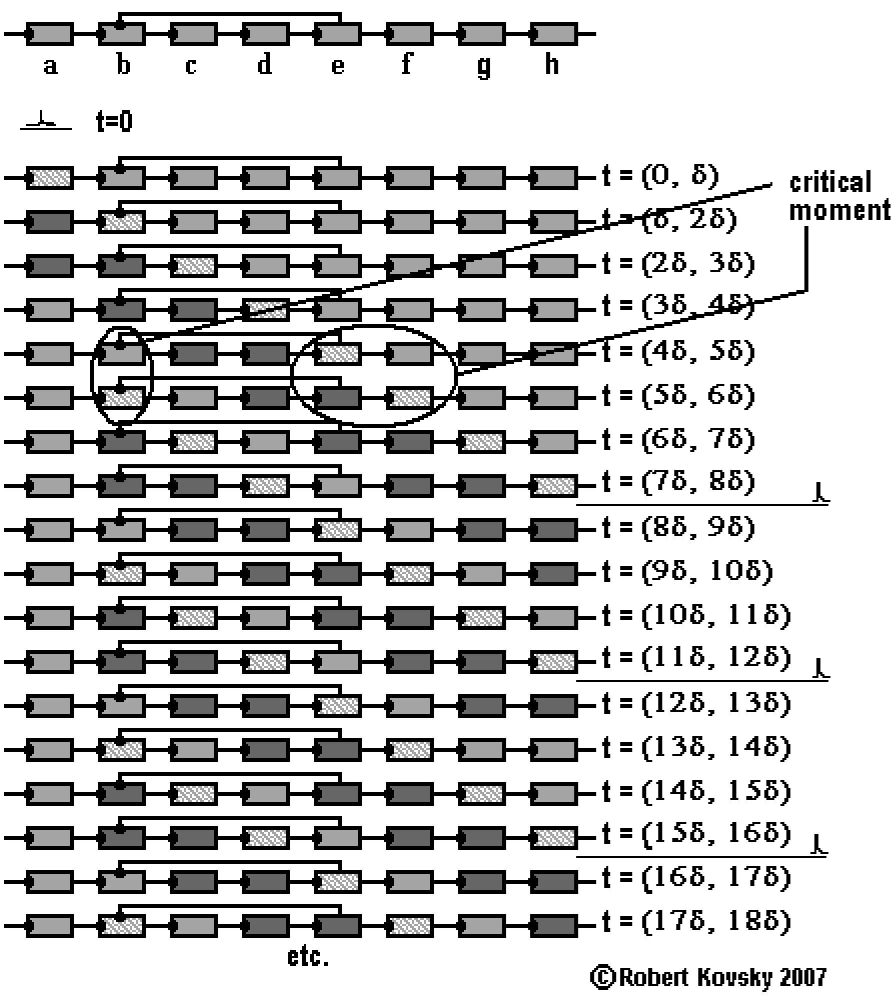
The new projection works the same as other projections; like electrical wires, projections can reach distant timing devices without change in function. All the timing devices in the pulse train generator operate according to the ***one-pulse trigger rule***: one pulse through ***any*** junction of a ready timing device will trigger the response process, even when the timing device has multiple inputs. In particular, when timing device b is ready, any pulse onto it, through either projection onto, will trigger the response process.

There are two projections from timing device e and the rule is that: every time timing device e pulses, it produces two pulses that are equally and simultaneously produced in both projections from timing device e. The ***equal-output rule*** applies throughout this presentation.

A central feature of the pulse train generator is a ***feedback ring*** made up of timing devices b, c, d and e, along with the projections that interconnect them. A pulse can circulate indefinitely in the feedback ring and generate a train of pulses through the output. A string of three timing devices – made up of timing devices f, g and h – serves as the output from the feedback ring, leading from timing device e. The single timing device a is the input to the feedback ring, projecting onto timing device b; and the single timing device a also called a "string." Hence, the pulse train generator is comprised of a feedback ring connected to an input string and to an output string.

Figure 4 shows what happens after a single pulse triggers the pulse train generator. In Figure 4, as before, timing intervals are set at β=2δ. Figure 4 is an example of a general class of ***pulse progress charts*** that also includes Figure 2. Pulse progress charts show conditions in an assembly of timing devices through a succession of periods of time. Each chart entry shows timing device conditions which are all constant during the designated period of time.

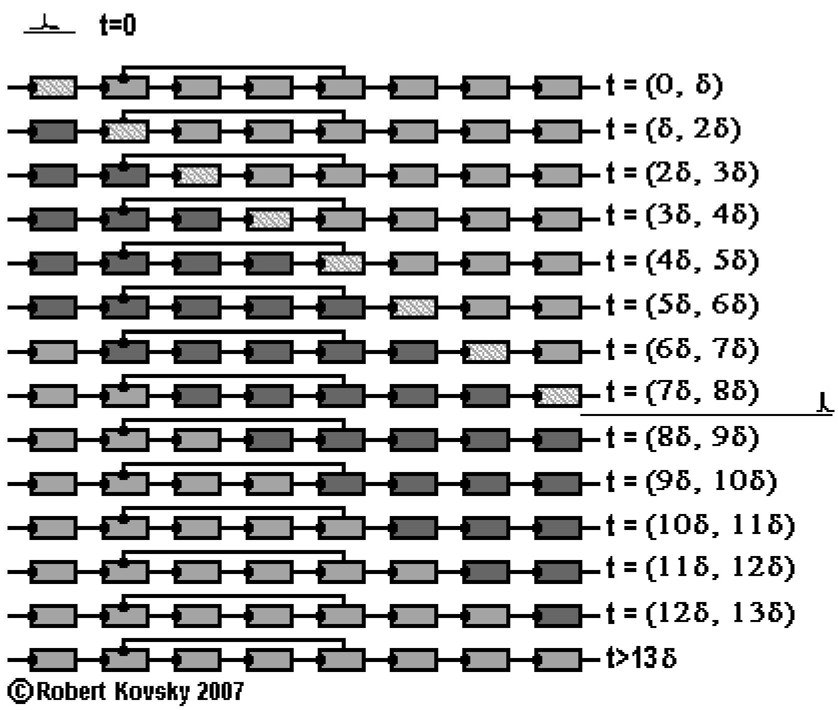
Figure 4: pulse train generator in operation (β=2δ)



For the first several clock ticks, the activity in Figure 4 is like that shown in Figure 2. The "critical moment" in Figure 4 occurs at t=5δ when timing device e produces two pulses; one pulse triggers timing device b through the new projection and one pulse triggers timing device f. The pulse projected onto timing device b becomes circulating activity in the ring. The ultimate difference 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 as output, with a period of 4δ between any two pulses in the sequence. In other words, the assembly shown in Figure 3 generates an ongoing ***pulse train*** with an indefinite length and with a period of time between pulses of 4δ.

If an attempt is made to operate the pulse train generator of Figure 3 when β=5δ, there is a result shown in Figure 5 that is different from that shown in Figure 4. A single pulse input into the pulse train generator produces a single pulse output; and activity thereafter ceases. The operational difference is that, in Figure 4, timing device b is in a ready condition at the critical moment t=5δ when timing device e produces a pulse onto timing device b; while, in Figure 5, timing device b is in a refractory condition at t=5δ and there is no response. The feedback ring becomes inactive.

Figure 5: inactive pulse train generator (β=5δ)



Examination shows that, for a single input pulse, the assembly shown in Figure 3 generates a pulse train like that shown in Figure 4 when β<3δ. On the other hand, for a similar single input pulse, the assembly produces only a single pulse output when β>3δ. Suppose δ is fixed at δ_0 while β is varied by the researcher continuously from $\beta<3\delta_0$ to $\beta>3\delta_0$, e.g., from $\beta=2.9\delta_0$ to $\beta=3.1\delta_0$. If the pulse train generator is producing a train of pulses when $\beta<3\delta_0$, that production will cease when, during the variation, β becomes equal to $3\delta_0$.

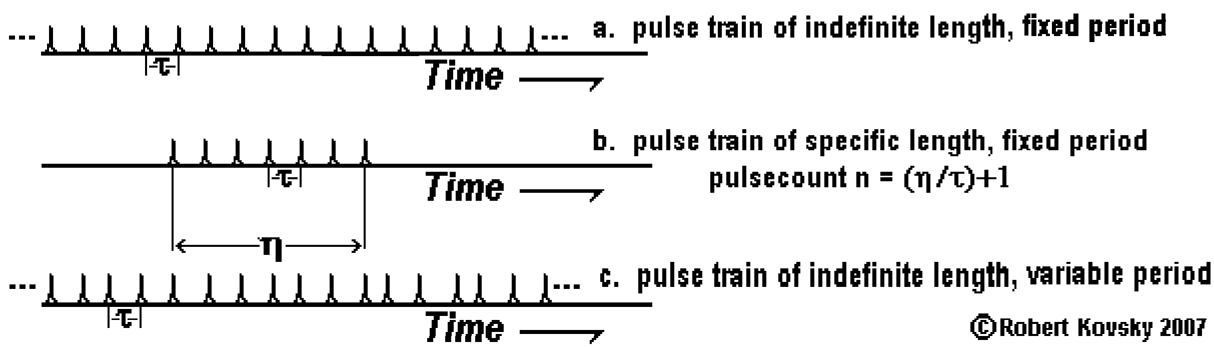
The principle is that (1) overall activity of the assembly is controlled by varying the timing interval β with respect to δ_0; and (2) imposing a continuous change in the relationship between timing intervals results in a discontinuous change in activity at a certain specific point, here at $\beta=3\delta_0$. I call such a discontinuous change a ***phase change*** because it resembles the change from liquid water to ice when the temperature passes through a specific point, 0° C. Such phase changes are an important general feature of assemblies and networks of timing devices.

4. Pulse Trains

A pulse train, e.g., that produced by the pulse train generator in Figure 4, is a chief form of signal organization in networks of timing devices. In the engineered organism presented below in section 10 that imitates sensory-motor activity of an animal, a pulse train drives a muscle-like fiber and the effective muscle-like activity is determined by the period of time between pulses. Generation and control of muscle-like activity is the chief goal and purpose of timing devices and assemblies and networks of timing devices.

A pulse train of indefinite length with a fixed period, e.g., that shown in Figure 6.a, has a beginning, but no end, as indicated by "...". The essential feature of such a pulse train is a fixed period of time, denoted τ, between any two pulses in the series. Equivalently, the pulse train can be described by a frequency $\nu = (1/\tau)$.

Figure 6: pulse trains



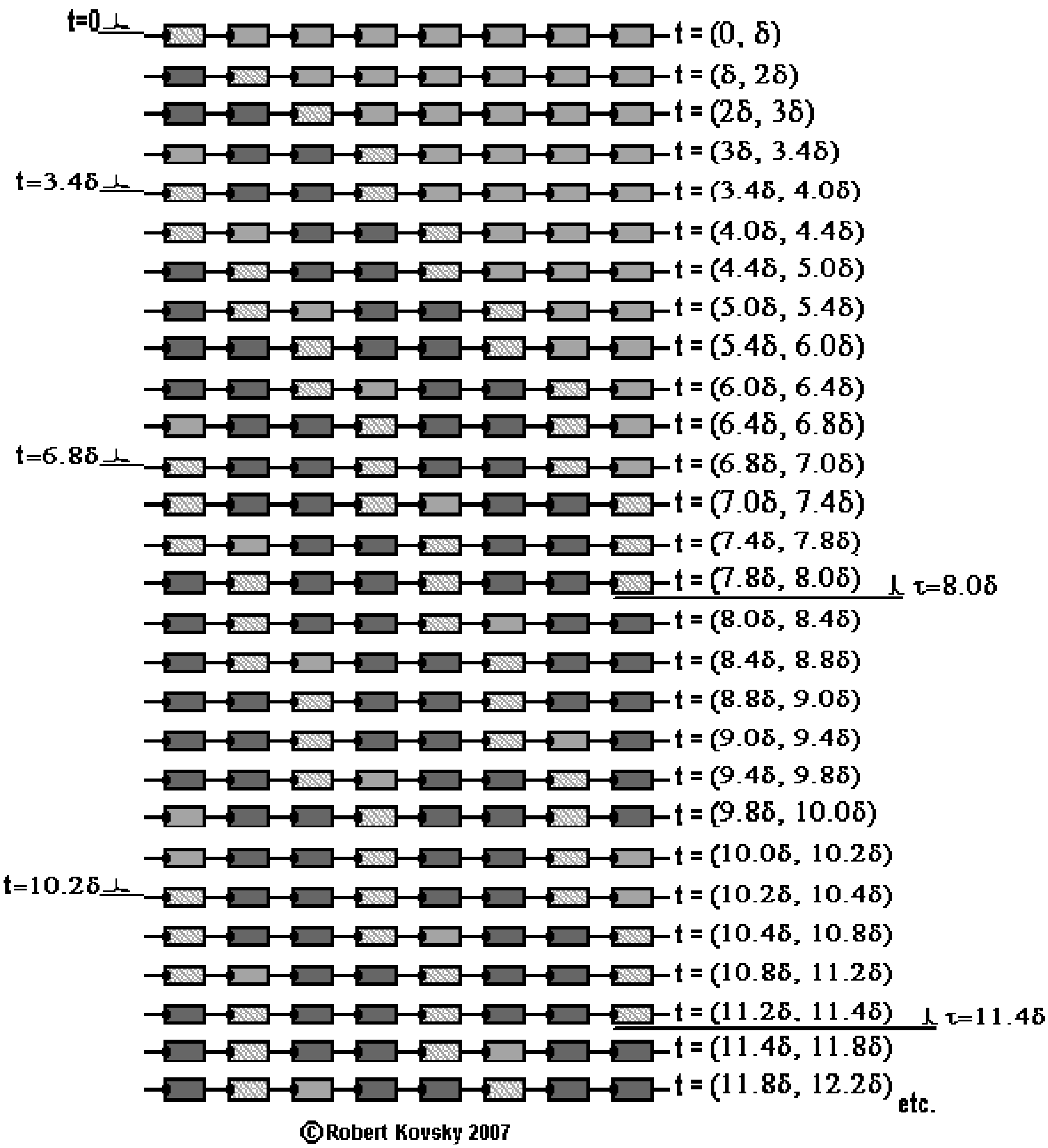
The pulse train of specific length in Figure 6.b has a specific duration, denoted by η, as well as a fixed period, τ, between pulses. The number of pulses in a pulse train of specific length is called the ***pulsecount*** and is denoted by n: $n=(\eta/\tau)+1$. A single pulse (as in Figure 1) is an extreme example of a pulse train, where $\eta=0$ and the pulsecount = 1.

Figure 6.c shows a pulse train of indefinite length with a variable period. The generation of such a pulse trains is discussed in section 6 in connection with modulation rules. There is a base period, τ, that varies according to circumstances.

Figure 7 is a pulse progress chart showing the passage of a pulse train through a string of simple timing devices where the period of the pulse train, with τ=3.4δ, is not an integral multiple of the timing device response period δ. Note that the output period is the same as the input period. As before, each line entry shows conditions fixed through the period of time stated; and each entry in the chart is identical to the previous entry except for rule-based changes. Although both input and output pulse trains are regular (with a period of 3.4δ), there are irregularities in the durations of periods of time in the presentation. Again, β=2.0δ which conveniently reduces the number of entries.

Figure 7: a pulse train passes through a string of timing devices

τ=3.4δ, β=2.0δ



Pulse progress charts can be reduced to a condensed typographical notation such as Figure 8 that is equivalent to the pulse progress chart shown in Figure 7. The letter 0 represents a timing device in the ready condition. The letter A represents a timing device in the responding condition. The letter Z represents a timing devices in the refractory condition

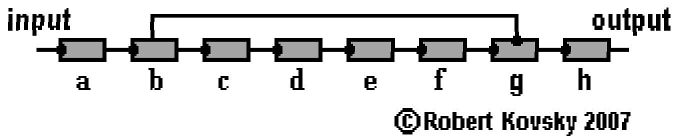
Figure 8: a pulse train passes through a string of timing devices, τ=3.4δ and β=2.0δ

```
|_____
   t=0  --A-0-0-0-0-0-0-0--      t=(0, δ)
        --Z-A-0-0-0-0-0-0--      t=(δ, 2.0δ)
        --Z-Z-A-0-0-0-0-0--      t=(2.0δ, 3.0δ)
|____   --0-Z-Z-A-0-0-0-0--      t=(3.0δ, 3.4δ)
 t=3.4δ --A-Z-Z-A-0-0-0-0--      t=(3.4δ, 4.0δ)
        --A-0-Z-Z-A-0-0-0--      t=(4.0δ, 4.4δ)
        --Z-A-Z-Z-A-0-0-0--      t=(4.4δ, 5.0δ)
        --Z-A-0-Z-Z-A-0-0--      t=(5.0δ, 5.4δ)
        --Z-Z-A-Z-Z-A-0-0--      t=(5.4δ, 6.0δ)
        --Z-Z-A-0-Z-Z-A-0--      t=(6.0δ, 6.4δ)
|____   --0-Z-Z-A-Z-Z-A-0--      t=(6.4δ, 6.8δ)
 t=6.8δ --A-Z-Z-A-Z-Z-A-0--      t=(6.8δ, 7.0δ)
        --A-Z-Z-A-0-Z-Z-A--      t=(7.0δ, 7.4δ)
        --A-0-Z-Z-A-Z-Z-A--      t=(7.4δ, 7.8δ)
        --Z-A-Z-Z-A-Z-Z-A--______t=(7.8δ, 8.0δ)_ | t=8.0δ
        --Z-A-Z-Z-A-0-Z-Z--      t=(8.0δ, 8.4δ)
        --Z-A-0-Z-Z-A-Z-Z--      t=(8.4, 8.8δ)
        --Z-Z-A-Z-Z-A-Z-Z--      t=(8.8δ, 9.0δ)
        --Z-Z-A-Z-Z-A-0-Z--      t=(9.0δ, 9.4δ)
        --Z-Z-A-0-Z-Z-A-Z--      t=(9.4δ, 9.8δ)
        --0-Z-Z-A-Z-Z-A-Z--      t=(9.8δ, 10.0δ)
        --0-Z-Z-A-Z-Z-A-0--      t=(10.0δ, 10.2δ)
|____   --A-Z-Z-A-Z-Z-A-0--      t=(10.2δ, 10.4δ)
t=10.4δ --A-Z-Z-A-0-Z-Z-A--      t=(10.4δ, 10.8δ)
        --A-0-Z-Z-A-Z-Z-A--      t=(10.8δ, 11.2δ)
        --Z-A-Z-Z-A-Z-Z-A--      t=(11.2δ, 11.4δ)
        --Z-A-Z-Z-A-0-Z-Z--______t=(11.4δ, 11.8δ)_| t=11.8 δ
        --Z-A-0-Z-Z-A-Z-Z--      t=(11.8δ, 12.2δ)
                                      etc.
```

Pulse progress charts are similar to charts used to track activities of cellular automata (See, e.g., S. Wolfram, *A New Kind of Science*); but cellular automata are based on an invariant clock tick and do not participate in phase changes like timing devices.

5. Pulse period selector

Figure 9: pulse period selector



The ***pulse period selector*** shown in Figure 8 passes or blocks a pulse train according to the period between pulses. Its function is like a bandpass filter in electronics that passes or blocks a periodic signal, e.g., a sine wave, according to the frequency.

The new feature in the pulse period selector is that timing device g is governed by the ***two-pulse trigger rule.*** All other timing devices in the assembly continue to be governed by the one-pulse trigger rule shown in Figure 1. The two outputs from timing device b are governed by the equal-output rule discussed in section 3.

Figure 10: two-pulse trigger rule

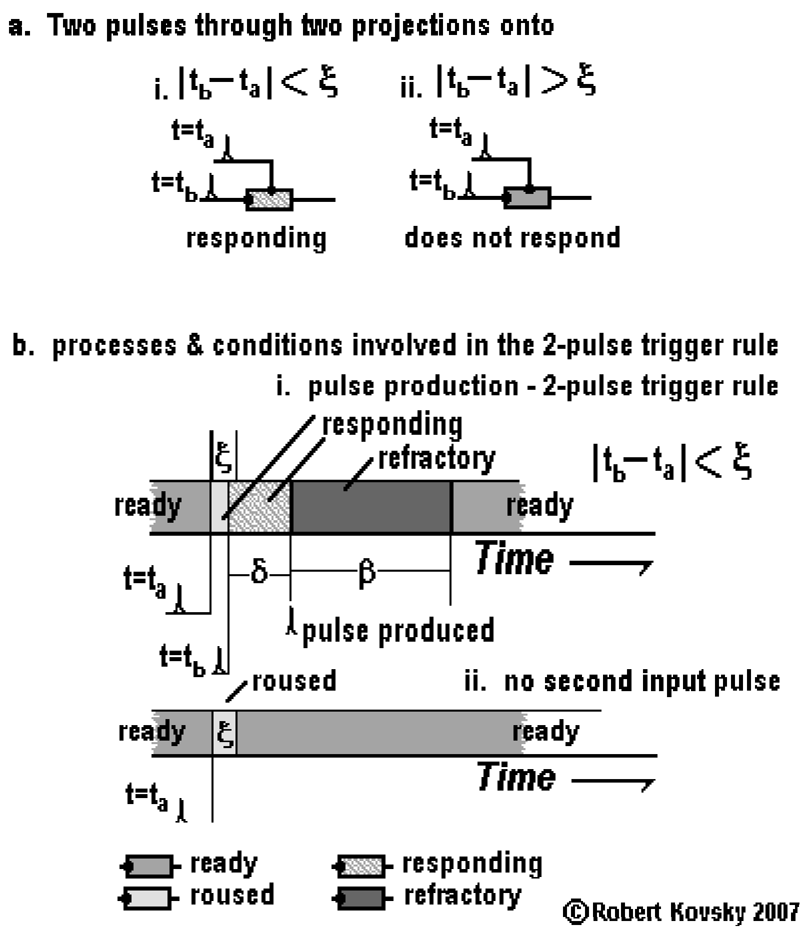


Figure 10.a shows a single timing device with two inputs where activity of the timing device is governed by the two-pulse trigger rule. The two-pulse trigger rule states that two pulses are required to trigger the response process and that both pulses must arrive at the timing device within a defined timing interval, ξ. It doesn't matter which arrives first. Suppose 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.

Figure 10.b shows the processes and conditions involved in the two-pulse trigger rule. A new condition is introduced, the ***roused condition***. If a timing device governed by the two-pulse trigger rule 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

condition changes to the responding condition. (See Figure 10.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 Figure 10.b.ii.)

In a timing device governed by the two-pulse trigger rule, there is an additional clock, the ***rousal clock*** that controls the start and termination of 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 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.

Next, the rousal process and roused condition are incorporated into the typographical notation previously introduced. The letter "B" denotes a timing device in the roused condition, like "A" denotes one in the responding condition. As before, an entry in a pulse progress chart shows the conditions of timing devices that are constant throughout the time interval that is part of the entry. Each change in conditions from one entry to the next is based on a rule.

Suppose that a pulse train with a period of 3.8δ is incident through the input of the pulse period selector, where δ is the uniform response period of timing devices in the selector. For a first example, the ξ of timing device g's two-pulse trigger rule is equal to 0.3δ. This means that if a second pulse arrives at timing device g within $\xi=0.3\delta$ of a first pulse, the response process in timing device g will be triggered, otherwise not. For this pulse train and setting of ξ, $\delta+\xi = 3.8\delta + 0.3\delta > 4.0\delta$, timing device g is triggered and the pulse train passes through the pulse period detector without change, other than a delay of 8δ and the reduction of the pulsecount by 1. The result is shown in Figure 11, overleaf. A different result results in the second example shown in Figure 12, where, all other things remain the same as in Figure 11, but ξ is changed to $\xi=0.1\delta$. Now, $\delta+\xi = 3.8\delta + 0.1\delta < 4.0\delta$; timing device g is not triggered; and no output emerges from the assembly.

The critical difference is at timing device 8. In Figure 11, timing device g is in the roused condition initiated by the first pulse when the second pulse arrives; in Figure 12, on the other hand, timing device g has returned to the ready condition when the second pulse arrives.

Figure 11: a pulse train (τ=3.8δ) passes through a pulse period selector (ξ=0.3δ, β=2.0δ)

```
              ┌─────────┐↓
          –a–b–c–d–e–f–g–h–  (β=2δ)
       |_____
     t=0  –A–0-0-0-0-0-0-0-              t=(0, δ)
          -Z-A-0-0-0-0-0-0-              t=(δ, 2δ)
          -Z-Z-A-0-0-0-B-0-              t=(2δ, 2.3δ)
          -Z-Z-A-0-0-0-0-0-              t=(2.3δ, 3δ)
      |____-0-Z-Z-A-0-0-0-0-             t=(3δ, 3.8δ)
  t=3.8δ  -A-Z-Z-A-0-0-0-0-              t=(3.8δ, 4.0δ)
          -A-0-Z-Z-A-0-0-0-              t=(4.0δ, 4.8δ)
          -Z-A-Z-Z-A-0-0-0-              t=(4.8δ, 5.0δ)
          -Z-A-0-Z-Z-A-0-0-              t=(5.0δ, 5.8δ)
          -Z-Z-A-Z-Z-A-B-0-              t=(5.8δ, 6.0δ)
          -Z-Z-A-0-Z-Z-A-0-              t=(6.0δ, 6.8δ)
          -0-Z-Z-A-Z-Z-A-0-              t=(6.8δ, 7.0δ)
      |____-0-Z-Z-A-0-Z-Z-A-             t=(7.0δ, 7.6δ)
  t=7.6δ  -A-Z-Z-A-0-Z-Z-A-              t=(7.6δ, 7.8δ)
          -A-0-Z-Z-A-Z-Z-A-__|           t=(7.8δ, 8.0δ)
          -A-0-Z-Z-A-0-Z-Z-  t=8.0δ      t=(8.0δ, 8.6δ)
          -Z-A-Z-Z-A-0-Z-Z-              t=(8.6δ, 8.8δ)
          -Z-A-0-Z-Z-A-Z-Z-              t=(8.8δ, 9.0δ)
          -Z-A-0-Z-Z-A-0-Z-              t=(9.0δ, 9.6δ)
          -Z-Z-A-Z-Z-A-B-Z-              t=(9.6δ, 9.8δ)
          -Z-Z-A-0-Z-Z-A-Z-              t=(9.8δ, 10.0δ)
          -Z-Z-A-0-Z-Z-A-0-              t=(10.0δ, 10.6δ)
          -0-Z-Z-A-Z-Z-A-0-              t=(10.6δ, 10.8δ)
      |____-0-Z-Z-A-0-Z-Z-A-             t=(10.8δ, 11.4δ)
 t=11.4δ  -A-Z-Z-A-0-Z-Z-A-              t=(11.4δ, 11.6δ)
          -A-0-Z-Z-A-Z-Z-A-___|          t=(11.6δ, 11.8δ)
          -A-0-Z-Z-A-0-Z-Z-  t=11.8δ     t=(11.8δ, 12.4δ)
          -Z-A-Z-Z-A-0-Z-Z-              t=(12.4δ, 12.6δ)
          -Z-A-0-Z-Z-A-Z-Z-              t=(12.6δ, 12.8δ)
          -Z-A-0-Z-Z-A-0-Z-              t=(12.8δ, 13.4δ)
          -Z-Z-A-Z-Z-A-B-Z-              t=(13.4δ, 13.6δ)
          -Z-Z-A-0-Z-Z-A-Z-              t=(13.6δ, 13.8δ)
          -Z-Z-A-0-Z-Z-A-0-              t=(13.8δ, 14.4δ)
          -0-Z-Z-A-Z-Z-A-0-              t=(14.4δ, 14.6δ)
       |___-0-Z-Z-A-0-Z-Z-A-             t=(14.6δ, 15.2δ)
 t=15.2   -A-Z-Z-A-0-Z-Z-A-              t=(15.2δ, 15.4δ)
          -A-0-Z-Z-A-Z-Z-A-___|          t=(15.4δ, 15.6δ)
          -A-0-Z-Z-A-0-Z-Z-  t=15.6δ     t=(15.6δ, 16.2δ)
          -Z-A-Z-Z-A-0-Z-Z-              t=(16.2δ, 16.4δ)
          -Z-A-0-Z-Z-A-Z-Z-              t=(16.4δ, 16.6δ)
          -Z-A-0-Z-Z-A-0-Z-              t=(16.6δ, 17.2δ)
          -Z-Z-A-Z-Z-A-B-Z               t=(17.2δ, 17.4δ)
          -Z-Z-A-0-Z-Z-A-Z               t=(17.4δ, 17.6δ) etc.
```

Figure 12: no passage through a pulse period selector of an input pulse train where τ=3.8δ and ξ=0.1δ, β=2.0δ

```
               ┌───────────↓
              -a-b-c-d-e-f-g-h-  (β=2δ)
           |_____
         t=0  -A-0-0-0-0-0-0-0-  t=(0, δ)
              -Z-A-0-0-0-0-0-0-  t=(δ, 2δ)
              -Z-Z-A-0-0-0-B-0-  t=(2δ, 2.1δ)
              -Z-Z-A-0-0-0-0-0-  t=(2.1δ, 3δ)
          |___-0-Z-Z-A-0-0-0-0-  t=(3δ, 3.8δ)
      t=3.8δ  -A-Z-Z-A-0-0-0-0-  t=(3.8δ, 4.0δ)
              -A-0-Z-Z-A-0-0-0-  t=(4.0δ, 4.8δ)
              -Z-A-Z-Z-A-0-0-0-  t=(4.8δ, 5.0δ)
              -Z-A-0-Z-Z-A-0-0-  t=(5.0δ, 5.8δ)
              -Z-Z-A-Z-Z-A-B-0-  t=(5.8δ, 5.9δ)
              -Z-Z-A-Z-Z-A-0-0-  t=(5.9δ, 6.0δ)
              -Z-Z-A-0-Z-Z-B-0-  t=(6.0δ, 6.1δ)
              -Z-Z-A-0-Z-Z-0-0-  t=(6.1δ, 6.8δ)
              -0-Z-Z-A-Z-Z-0-0-  t=(6.8δ, 7.0δ)
          |___-0-Z-Z-A-0-Z-0-0-  t=(7.0δ, 7.6δ)
      t=7.6δ  -A-Z-Z-A-0-Z-0-0-  t=(7.6δ, 7.8δ)
              -A-0-Z-Z-A-Z-0-0-  t=(7.8δ, 8.6δ)
              -Z-A-Z-Z-A-0-0-0-  t=(8.6δ, 8.8δ)
              -Z-A-0-Z-Z-A-0-0-  t=(8.8δ, 9.6δ)
              -Z-Z-A-Z-Z-A-B-0-  t=(9.6δ, 9.7δ)
              -Z-Z-A-Z-Z-A-0-0-  t=(9.7δ, 9.8δ)
              -Z-Z-A-0-Z-Z-B-0-  t=(9.8δ, 9.9δ)
              -Z-Z-A-0-Z-Z-0-0-  t=(9.9δ, 10.6δ)
              -0-Z-Z-A-Z-Z-0-0-  t=(10.6δ, 10.8δ)
          |___-0-Z-Z-A-0-Z-0-0-  t=(10.8δ, 11.4δ)
     t=11.4δ  -A-Z-Z-A-0-Z-0-0-  t=(11.4δ, 11.6δ)
              -A-0-Z-Z-A-Z-0-0-  t=(11.6δ, 11.8δ)
              -A-0-Z-Z-A-0-0-0-  t=(11.8δ, 12.4δ) etc.
```

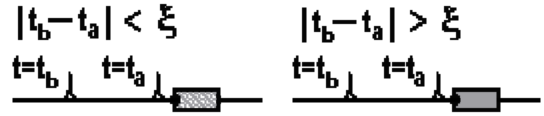
Examination shows that a pulse train will pass through the pulse period selector if the period between pulses, τ in the pulse train, is within limits defined as $(4.0\delta - \xi)<\tau<(4.0\delta + \xi)$. Hence, the pulse period selector resembles a bandpass filter in electronics.

Suppose the pulse period selector is passing a pulse train of period τ=3.8δ and operating with an initial ξ=0.3δ; and then suppose that the researcher progressively decreases ξ. As ξ passes from ξ>0.2δ to ξ<0.2δ, the output pulse train ceases. This behavior is like that noted at the conclusion of section 4, where "imposing a continuous change in a relationship between timing intervals results in a discontinuous change in activity at a certain specific point." There, the specific point was β=3δ; here the specific point is ξ=0.2δ. These changes belong to the class of phase changes, like those seen in materials like water where a continuous variation in temperature controls discontinuous changes in the overall condition, e.g., changing liquid water to ice.

A different kind of pulse period selector is shown in Figure 13, where the timing device has only a single input and is governed by the two-pulse trigger rule. The two-pulse rule is the same as that shown in Figure 10.b, it is the projections that are different.

When a second pulse arrives within ξ of a first pulse, the response process is triggered, but otherwise not. The operative rousal period in Figure 13 is longer than that in Figure 10. E.g., to pass a pulse train where τ=4.0δ, a satisfactory value for ξ is ξ=4.1δ.

Figure 13: another pulse period selector



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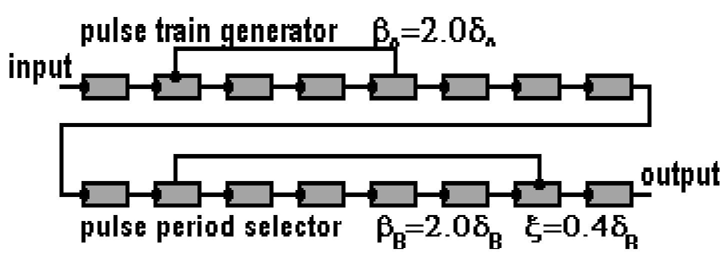
There are significant functional differences between the pulse period selector shown in Figure 10 and that shown in Figure 13. The selector in Figure 10 produces output when the input is a pulse train with a period in a band $[(4.0\delta - \xi) < \tau < (4.0\delta + \xi)]$ while the selector in Figure 13 produces output when the input is a pulse train with a period less than the rousal period or $\tau < \xi$. The output of the selector shown in Figure 10 is a pulse train with the same period as the input train and with an output pulsecount that is the same as the input pulsecount, less 1 pulse. As to the selector shown in Figure 13, if $(\delta + \beta) < \tau$, the output is a pulse train with double the period and half the pulsecount, thus halving the frequency of the pulse train. If $(\delta + \beta) > \tau$, the period of any output pulse train will be longer and the pulsecount less when $(\delta + \beta) < \tau$.

A different kind of phase change is shown in Figure 14, where the output of a phase train generator (Figure 3) becomes the input to a pulse period selector (Figure 9). In other words, two distinct assemblies are connected into a network. The common response period of the pulse train selector, δ_A, is distinct from the common response period of the pulse period selector, δ_B.

Figure 14: pulse train generator connected to pulse period selector



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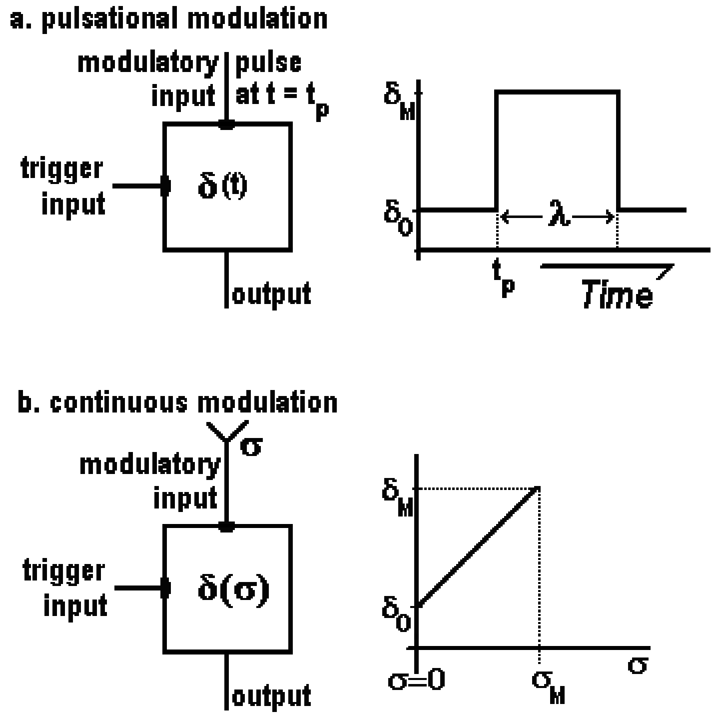
If δ_A=δ_B, the pulse train that is generated will have a period of τ=4.0δ_A and will pass through the pulse period selector as previously shown. Suppose δ_A=0.8δ_B; then the pulse train incident upon the pulse period selector will have a period of τ=4.0δ_A=3.2δ_B. If ξ=0.4δ_B as shown in Figure 14, such a pulse train will not pass through. Examination shows that, when ξ=0.4δ_B, the pulse train will pass through if 0.9δ_B <δ_A<1.1δ_B, but not otherwise. E.g., there will be a phase change as δA varies from a bit less than 1.1δ_B to a bit more than 1.1δ_B. The pulse train generator will continue generating pulse trains throughout the variation but the variation will change the overall activity of the network, especially at the output.

6. Modulation rules

Figure 15 shows how modulation rules apply to a timing device. Figure 15.a shows pulsational modulation. A pulse at t= t_p incident onto the modularity input changes the timing interval δ for a duration of time, λ, the ***modulation period***. If an input pulse is incident onto the trigger input at any time between t_p and ($t_p + \lambda$), the response period of the timing device will be δ_M; otherwise the response period will be δ_0. If a second modulatory pulse arrives during the modulation period, λ, the modified δ –i.e., δ_M – will continue to be effective for the modulation period λ from the time of the second pulse.

Figure 15: modulation rules



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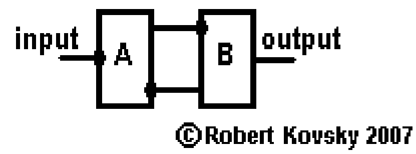
For example, suppose all the timing devices in the pulse train generator in Figure 14 are outfitted with common modularity inputs of the kind shown in Figure 15.a, suppose the network has a base level of δ_A=δ_B and suppose δ_M=1.2δ_A in the pulse train generator. If a modularity pulse is input onto all the timing devices of the pulse train generator, the result will be an interruption in output from the pulse period selector for the modulation period λ, resuming thereafter.

Modulation rules are also used for sensory activity and the modulation rule in Figure 15.b is defined to show such a use. There is a modulatory input carrying a signal σ that is incident upon the timing device and the effect is to cause a continuous variation in δ that depends on σ. When σ is 0, $\delta = \delta_0$, a base level. As σ increases, δ becomes larger, reaching a maximum, denoted by δ_M, when σ is at its maximum level, denoted by σ_M. That is, the modularity input (sensation) causes the timing device to respond more slowly. The operative value of δ is fixed at the instant a pulse is incident onto the trigger input of a ready timing device and the response period commences. There is no modulation period; rather, the model has continuous variation.

7. Coupled timing devices

Suppose we have two timing devices reciprocally connected as shown in Figure 16, called ***coupled timing devices***. Both timing devices use the one-pulse trigger rule: a pulse incident onto timing device A through either projection onto will trigger the response process. A pulse produced by timing device B is governed by the equal-output rule discussed in section 3.

Figure 16: coupled timing devices



The assembly of coupled timing devices in Figure 16 is an extreme example of a pulse train generator (Figure 3), one where the feedback ring has only two timing devices.

For a more detailed analysis, let β_A and δ_A denote the timing intervals of timing device A; and let β_B and δ_B denote those of timing device B. Figure 17.a shows how the coupled timing devices respond to a pulse at t=0 when β_A=β_B, δ_A=δ_B and $\beta<\delta$, the case of "symmetric repetition." For convenience, each period of time refers to a standard unit according to the global time variable measured by the realtime clock, e.g., "1.0" means "1.0 msec." After timing device A produces a pulse, it will become ready before timing device B produces the next pulse; therefore, each timing device will trigger the other repeatedly. The result is a pulse train with a period of 2.0. Hence, a pair of coupled timing devices acts as a ***pacemaker***.

Figure 17.b shows how things are different when $\beta>\delta$; timing device A is refractory when timing device B produces a pulse – so everything comes to a halt after passage of the original pulse.

Figure 17: coupled timing devices and pulse train generation

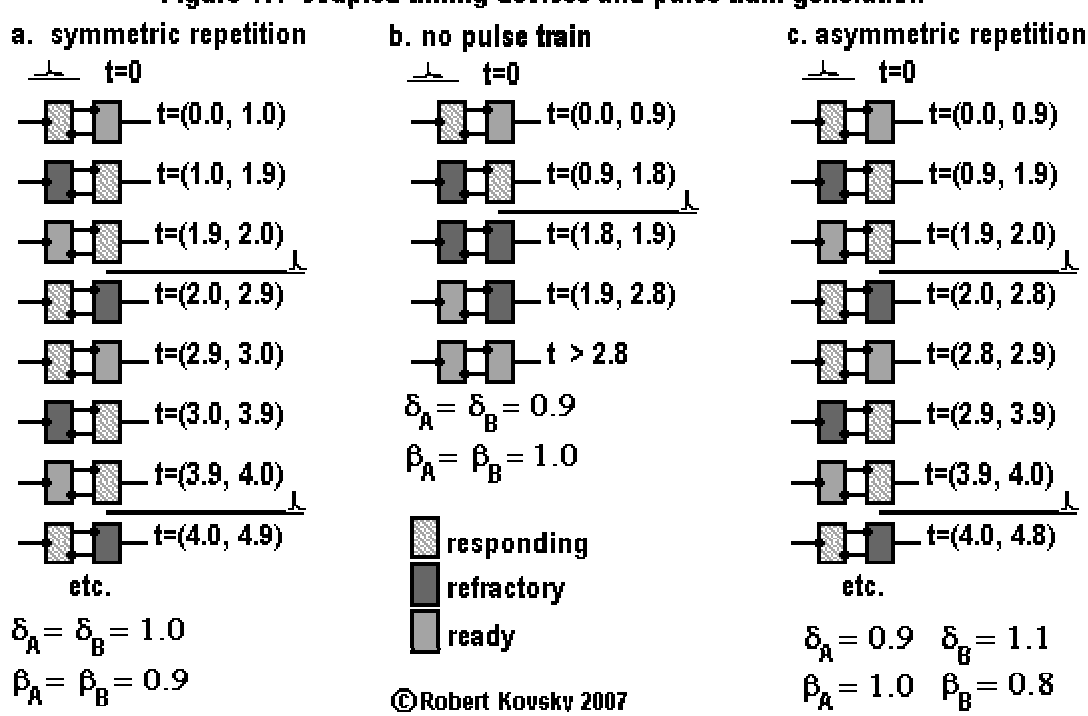
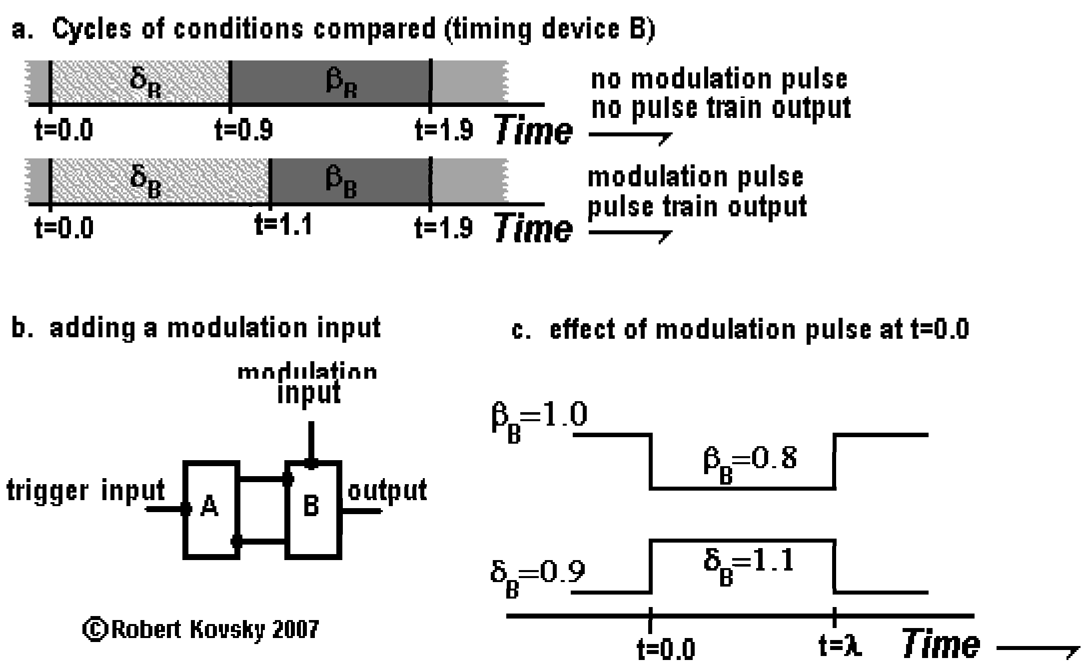


Figure 17.c shows how variations in timing intervals control pulse patterns: start with the coupled timing devices in operation with the timing intervals shown in Figure 17.b. Leaving timing device A untouched, change the timing intervals of timing device B to those shown in Figure 17.c to get the new kind of response, "asymmetric repetition," that can produce a pulse train identical to that shown in Figure 17.a.

Figure 18.a compares the activity of timing device B used in Figure 17.b with that used in Figure 17.c, showing the respective cycles of conditions. In both cases, $\delta_B+\beta_B=1.9$ but the proportions are different.

Now suppose a slightly different and new modulation rule is defined to alter the proportions of timing intervals for an interval of time, λ. The new modulation rule increases δ_B and decreases β_B equally but in opposite ways (Figure 18.a). As shown in Figure 18.b, a modulation input governed by the new modulation rule is added to timing device B. The effect of a pulse through the modulation input (the modulation pulse) is shown in Figure 18.c. There is a ***shifting*** of a period of time from the timing interval β of the refractory condition to that of δ, the responding condition. This shift changes the situation from that shown in Figure 15.b to that shown in Figure 15.c. The shifted period of time is relatively small but it changes the overall activity of the pair of coupled timing devices, constituting a phase change.

Figure 18: a modulation rule for controlling coupled timing devices



Suppose the assembly in Figure 18.b has the δ and β timing intervals of the assembly shown in Figure 17.b and, at t=0, there is both a pulse incident onto timing device A through the trigger input and also a pulse incident through the modulation input. The assembly operates like that shown in Figure 17.c from t=0 to t=λ. The assembly will produce a pulse train with a pulsecount approximately equal to λ/τ (in the example τ=2.0).

8. A string of coupled timing devices

Figure 19 shows a string of coupled timing devices with an added trigger input projection onto timing device E. All timing devices operate according to the one-pulse trigger rule and equal-output rule.

Figure 19: a string of coupled timing devices

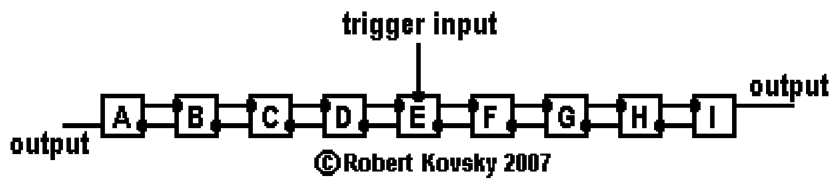


Figure 20 uses the typographical notation to show the activity of the string of coupled timing devices with an input pulse to timing device E at t=0, with β=0.9δ. As before, "0" stands for a ready timing device; "A" stands for a timing device in the responding condition; and "Z" stands for a timing device in the refractory condition.

Figure 20: activity of a string of coupled timing devices in response to an input pulse at t=0 with β=0.9δ

```
                 input
                   |
        -A=B=C=D=E=F=G=H=I-    β=0.9δ

        -0=0=0=0=0=0=0=0=0-            t<0
        -0=0=0=0=A=0=0=0=0-            t=(0, δ)
        -0=0=0=A=Z=A=0=0=0-            t=(δ, 1.9δ)
        -0=0=0=A=0=A=0=0=0-            t=(1.9δ, 2.0δ)
        -0=0=A=Z=A=Z=A=0=0-            t=(2.0δ, 2.9δ)
        -0=0=A=0=A=0=A=0=0-            t=(2.9δ, 3.0δ)
        -0=A=Z=A=Z=A=Z=A=0-            t=(3.0δ, 3.9δ)
        -0=A=0=A=0=A=0=A=0-            t=(3.9δ, 4.0δ)
        -A=Z=A=Z=A=Z=A=Z=A-            t=(4.0δ, 4.9δ)
    |   -A=0=A=0=A=0=A=0=A-    |       t=(4.9δ, 5.0δ)
t=5.0δ  -Z=A=Z=A=Z=A=Z=A=Z-  t=5.0δ    t=(5.0δ, 5.9δ)
        -0=A=0=A=0=A=0=A=0             t=(5.9δ, 6.0δ)
        -A=Z=A=Z=A=Z=A=Z=A-            t=(6.0δ, 6.9δ)
    |   -A=0=A=0=A=0=A=0=A-    |       t=(6.9δ, 7.0δ)
t=7.0δ  -Z=A=Z=A=Z=A=Z=A=Z-  t=7.0δ    t=(7.0δ, 7.9δ)
        -0=A=0=A=0=A=0=A=0             t=(7.9δ, 8.0δ)

                      repeating thereafter, every 2δ
```

When β>δ, there is a different activity, as shown in Figure 21: one input pulse onto timing device E produces just one output pulse through each of the two outputs.

Figure 21: activity of a string of coupled timing devices in response to an input pulse at t=0 with β=1.1δ

```
                 input
                   |
        -A=B=C=D=E=F=G=H=I-   β=1.1δ

        -0=0=0=0=0=0=0=0=0-           t<0
        -0=0=0=0=A=0=0=0=0-           t=(0, δ)
        -0=0=0=A=Z=A=0=0=0-           t=(δ, 2.0δ)
        -0=0=A=Z=Z=Z=A=0=0-           t=(2.0δ, 2.1δ)
        -0=0=A=Z=0=Z=A=0=0-           t=(2.1δ, 3.0δ)
        -0=A=Z=Z=0=Z=Z=A=0-           t=(3.0δ, 3.1δ)
        -0=A=Z=0=0=0=Z=A=0-           t=(3.1δ, 4.0δ)
        -A=Z=Z=0=0=0=Z=Z=A-           t=(4.0δ, 4.1δ)
    |___-A=Z=0=0=0=0=0=Z=A-___|       t=(4.1δ, 5.0δ)
t=5.0δ  -Z=Z=0=0=0=0=0=Z=Z-  t=5.0δ   t=(5.0δ, 5.1δ)
        -Z=0=0=0=0=0=0=0=Z-           t=(5.1δ, 6.1δ)
        -0=0=0=0=0=0=0=0=0-           t>6.1δ
```

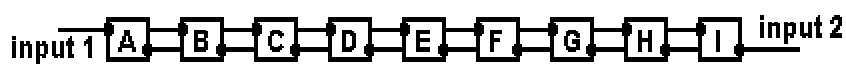
Activity when β<δ (Figure 20) is distinctly different from that when β>δ (Figure 21). If β<δ, once any timing device is triggered and the signals spread, the timing devices will generate pulses indefinitely with a period of 2.0δ in an oscillatory fashion like that of Figure 20.

9. Differentiation behavior in a string of coupled timing devices

In this section, development reaches a point where activity can be described as ***behavior***. Behavior is activity that is characterized by useful functionality and the activity shown in this section merits the change in terminology. The functionality is ***differentiation with resulting output***. Two pulse trains are incident onto a string of coupled timing devices, one onto the left end and one onto the right end. Each pulse train has its own pulsecount, n_l onto the left end and n_r onto the right end. There is an output from one side or the other. If $n_l > n_r$, the output is a pulse train with pulsecount $n_l - n_r$, with the output exiting from the right side; if $n_r > n_l$, the output is a pulse train with pulsecount $n_r - n_l$, with the output exiting from the left side. To complete the assembly, outputs must be attached to each end of the string; but, for purposes of presentation, differentiating activity is shown first.

Figure 22 shows a string of coupled timing devices with two inputs, one at each end of the timing device. For typographical clarity, input 1 is onto the left end and input 2 is onto the right end.

Figure 22: a string of coupled timing devices with two inputs



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Using the typographical notation to represent activity of a string of coupled timing devices with $\beta=2\delta$, Figure 23 shows that a pulse incident through input 1 and a pulse incident through input 2 will cancel or annihilate each other. Such cancellation does not depend on details of timing, only on the pulsecount. To illustrate this fact, the pulse through input 1 occurs at t=0 and the pulse through input 2 occurs at t=δ, so that cancellation occurs away from the center.

Figure 23: behavior of a string of coupled timing devices in response to single input pulse incident at each end (constraint β=2δ)

```
input 1–A=B=C=D=E=F=G=H=I–input 2
          –0=0=0=0=0=0=0=0=0– t<0
          –A=0=0=0=0=0=0=0=0– t=(0, δ)
          –Z=A=0=0=0=0=0=0=A– t=(δ, 2δ)
          -Z=Z=A=0=0=0=0=A=Z- t=(2δ, 3δ)
          -0=Z=Z=A=0=0=A=Z=Z- t=(3δ, 4δ)
          -0=0=Z=Z=A=A=Z=Z=0- t=(4δ, 5δ)
          -0=0=0=Z=Z=Z=Z=0=0- t=(5δ, 6δ)
          -0=0=0=0=Z=Z=0=0=0- t=(6δ, 7δ)
          -0=0=0=0=0=0=0=0=0- t>7δ
```

Cancellation at t=5δ occurs because a timing device is not responsive to another pulse while it is in the responding condition (see section 1). As the reader can verify, if pulses were incident onto both input 1 and input 2 at t=0, they would merge into a single responding condition at timing device E and timing device E would be surrounded by refractory timing devices when it produces a pulse so that the pulse would be unproductive.

Figure 24 shows the differential result, for two pulse trains of different lengths and with different periods. In Figure 24, the pulse train incident from the left onto input 1 has two pulses and a period of 5δ between pulses and the pulse train incident from the right onto input 2 has three pulses and a period of 4δ between pulses. The pulse train incident from the left begins at t=0 and the pulse train incident from the right begins at t=δ. The constraint β=2δ applies to all timing devices in the string. The differential 3-2=1 results in a single pulse that travels to the end of the string at the left; because there is no output, it ends there.

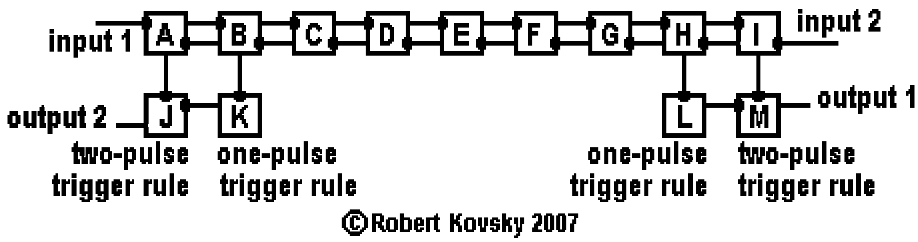
Figure 24: behavior of a string of coupled timing devices in response to pulse trains incident at two ends (constraint β=2δ)

```
input 1 –A=B=C=D=E=F=G=H=I–  input 2

        –0=0=0=0=0=0=0=0=0–       t<0
   |___ –A=0=0=0=0=0=0=0=0–       t=(0, δ)
    t=0 -Z=A=0=0=0=0=0=0=A- ___| t=(δ, 2δ)
        -Z=Z=A=0=0=0=0=A=Z- t=1δ t=(2δ, 3δ)
        -0=Z=Z=A=0=0=A=Z=Z-      t=(3δ, 4δ)
        -0=0=Z=Z=A=A=Z=Z=0-      t=(4δ, 5δ)
   |___ -A=0=0=Z=Z=Z=Z=0=A- ___| t=(5δ, 6δ)
   t=5δ -Z=A=0=0=Z=Z=0=A=Z- t=5δ t=(6δ, 7δ)
        -Z=Z=A=0=0=0=A=Z=Z-      t=(7δ, 8δ)
        -0=Z=Z=A=0=A=Z=Z=0-      t=(8δ, 9δ)
        -0=0=Z=Z=A=Z=Z=0=A- ___| t=(9δ, 10δ)
        -0=0=0=Z=Z=Z=0=A=Z- t=9δ t=(10δ, 11δ)
        -0=0=0=0=Z=Z=A=Z=Z-      t=(11δ, 12δ)
        -0=0=0=0=0=A=Z=Z=0-      t=(12δ, 13δ)
        -0=0=0=0=A=Z=Z=0=0-      t=(13δ, 14δ)
        -0=0=0=A=Z=Z=0=0=0-      t=(14δ, 15δ)
        -0=0=A=Z=Z=0=0=0=0-      t=(15δ, 16δ)
        -0=A=Z=Z=0=0=0=0=0-      t=(16δ, 17δ)
        -A=Z=Z=0=0=0=0=0=0-      t=(15δ, 18δ)
        -Z=Z=0=0=0=0=0=0=0-      t=(18δ, 19δ)
        -Z=0=0=0=0=0=0=0=0-      t=(19δ, 20δ)
        -0=0=0=0=0=0=0=0=0-      t>20δ
```

Figure 25 shows an assembly of timing devices where two outputs are attached to the two ends of a string of coupled timing devices that is identical to that shown in Figure 22. The two outputs (one made up of timing devices J and K; and the other made up of timing devices L and M) have a single, mirrored design. All the timing devices in the outputs (J, K, L, M) have the same values of δ and β as the timing devices in the original string (A through I) and, as before, $\beta=2\delta$. All the timing devices in the larger-scale assembly are governed by the equal-output rule. The timing devices in the outputs governed by the "one-pulse trigger rule" – K and L – are identical to those in the string except for having only one projection onto and only one projection from timing devices K and L. The only additional change in timing devices J and M is that they are governed by a two-pulse trigger rule (see section 5). Whenever the two-pulse trigger rule is activated in this assembly, two pulses are always simultaneously incident onto timing device J or timing device M, so the timing interval ξ is not critical so long as it is less than 2δ. Say $\xi=0.1\delta$.

Figure 25: string of coupled timing devices with two inputs and attached outputs



The behavior of the assembly in Figure 25 is straightforward. Suppose a pulse is introduced through input 1. When timing device A produces a pulse, that pulse will trigger timing device B but not timing device J because timing device J requires two pulses to trigger it. When timing device B produces a pulse after a period δ, timing device K will be triggered; but the pulse later produced by timing device K will not trigger timing device J because timing device J requires two pulses that arrive within ξ for J to trigger and that does not occur. See Figure 10.b.ii.

Eventually, the pulse introduced through input 1 will travel to end of the string. When timing device H produces a pulse, that pulse will trigger both timing device L and timing device I. Timing devices I and L will produce pulses at the same moment and the combination will trigger timing device M, activating the two-pulse trigger rule, so timing device M will produce an output pulse after another response period δ. Hence, if the only input is a pulse onto input 1, the assembly will produce a pulse through output 1. Likewise, if the only input is a pulse onto input 2, the assembly will produce a pulse through output 2.

Further, the differential behavior discussed in connection with Figure 21 will generate appropriate outputs. If a pulse train with n_l pulses is incident onto input 1 and one with n_r pulses is incident onto input 2, and if $n_l>n_r$, a pulse train with pulsecount $n_l–n_r$ will be produced through output 1 and nothing will happen at output 2. If $n_r>n_l$, the output will be a mirror of the first case and $n_r–n_l$ pulses will be produced through output 2 and nothing will happen at output 1.

The assembly shown in Figure 25 can also operate with pulse trains of indefinite length that have distinct fixed periods, τ_1 and τ_2, or, alternatively, distinct fixed frequencies, ν_1 and ν_2. (See section 5.) Then the assembly generates a pulse train with a differential fixed frequency. If a pulse train with fixed frequency ν_l is incident through input 1 and a pulse train with fixed frequency ν_2 is incident through input 2, and if $\nu_l > \nu_r$, a pulse train with fixed frequency $\nu_l - \nu r$ will be produced through output 1 and nothing will happen at output 2. The behavior can also be generalized to pulse trains with variable frequencies but the results depend on the details. What is important is that the periods remain within a constrained range, for example between 10/sec and 20/sec, so that pulses from opposite ends actually meet and cancel.

10. An engineered organism

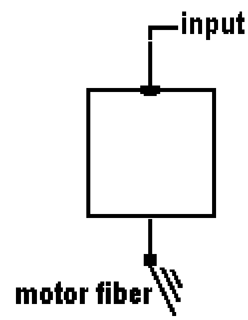
An engineered organism is a network of timing devices that engages in sensory-motor behavior where muscle-like activity is controlled by sensory influences. The engineered organism is like a simple biological entity, e.g., a jellyfish, that moves through a supporting medium, like the ocean. Movement is responsive to variations in the environmental influences, e.g., light, gravity or significant molecules that have the nature of odors or tastes.

The network of timing devices shown in this section controls motor activity to direct the engineered organism with respect to the sensation, e.g., to move toward a source of light.

The engineered organism is constituted by assemblies previously discussed plus a ***motor unit*** that converts timing device pulses into muscle-like activity.

Figure 26 shows a simple motor unit. A ***motor fiber*** attached to a timing device twitches in responses to pulses that are incident onto the time device through an input. That is, each pulse that is incident onto the motor unit through the input causes the motor fiber to twitch forcefully in the lateral direction indicated. After twitching, the motor fiber returns to the center. In the engineered organism, the motor fiber extends into a supporting medium (such as the ocean) and resembles a tentacle or flagellum that is part of a biological organism. A twitching motor fiber pushes the engineered organism in the opposite direction.

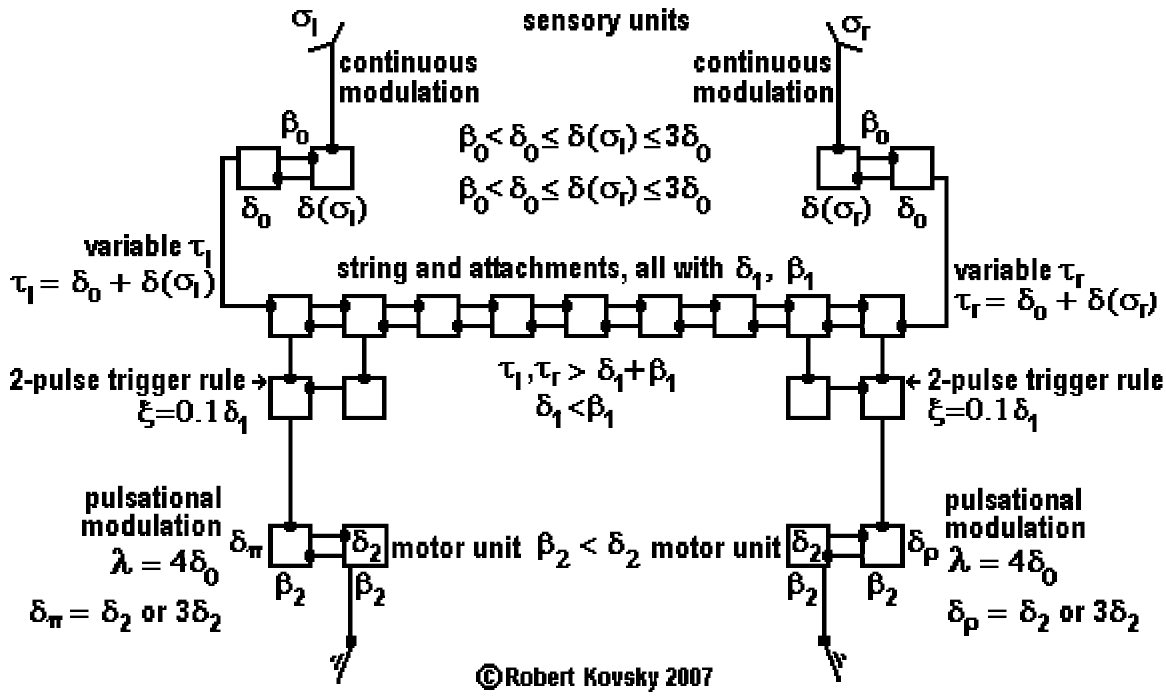
Figure 26: motor unit



A sensory-motor network for a very simple engineered organism is shown in Figure 27. The motor units are continuously driven by pacemakers. Sensations – e.g., light, or a chemical, such as food – are detected at the two sensory units and the difference –resulting from cancellation activity in the central string of coupled timing devices with attached outputs (Figure 25) – results in modulation of the pacemaker driving one of the motor units but not the other.

If there is no sensation, a sensory pacemaker generates a pulse train with a period of $\tau=2\delta_0$; if a maximum sensation, the period of the pulse train is $\tau=4\delta_0$. (Combining concepts shown in Figures 15 and 17.) E.g., if there is maximum sensation on the left and no sensation on the right, τ_l will be $4\delta_0$ and τ_r will be $2\delta_0$. After cancellations in the string, there will be a pulse train of modulation pulses with period $4\delta_0$ onto the left motor pacemaker, slowing it so that the engineered organism turns toward the left.

Figure 27: sensory-motor network for an engineered organism



At each motor unit, there are repeated contractions of the motor fiber driven by a pacemaker that includes a modulated timing device. (See Figure 17.) If there is no modulation pulse onto the modulated timing device, the period of the contractions is $2\delta_2$. If the modulated timing device is under the influence of a modulation pulse, the period of the contractions is $4\delta_2$. The length of the modulation period λ (see Figure 15.a) is set at $4\delta_0$ so that, if the difference in sensations is maximum, a successor modulation pulse will arrive at the modulated timing device just as effect of the predecessor modulation pulse ends. If the difference in sensations is less than maximum, the motor unit coupled with the modulated timing device will alternate between contractions with a period of $2\delta_2$ and those with a period of $4\delta_2$. The less sensation, the less the turning effect. When the sensations are balanced, there is complete cancellation in the central string of coupled timing devices, neither motor pacemaker is modulated and it is full speed ahead.

Constraints on operations are set forth in the central area of Figure 27, e.g., $\beta_0<\delta_0<\delta(\sigma_l)<3\delta_0$. Using δ_M from section 6, $\delta_M=3\delta_0$. For pacemaker operations (Figure 17), β_0 must be less than δ_0. Hence, $\delta_0\leq\delta(\sigma)\leq3\delta_0$ for both σ_l and σ_r.

In the central string, β_1 must be greater than δ_1. (See Figures 20 and 21.) The response period of the central string, δ_1, must be shorter than δ_0 — because $\delta_1<\beta_1$ (Figures 20 and 21), because, as to each input pulse train, $\tau>(\delta_1+\beta_1)$ (Figure 1) and because the shortest-period input pulse train has $\tau=2\delta_0$. The limits on these constraints occurs when $\delta_1=\beta_1$ and $\tau=(\delta_1+\beta_1)$; hence, at the limit, $2\delta_0=\tau=\delta_1+\beta_1=2\delta_1$. There is also a constraint in the other direction limiting how fast the central string timing devices can be in comparison to the sensor timing devices and $\delta_1>\delta_0/4$ satisfies that constraint, based on the string of 9 timing devices. (There is a bit to spare with this figure but the derivation is complex so it is left as an exercise for the reader.) Hence $\delta_0/4<\delta_1<\delta_0$ and β_1 must be adjusted to fit the constraints $\beta_1>\delta_1$ and $2\delta_0>\delta_1+\beta_1$. E.g., if $\delta_1=\delta_0/2$ and $\beta_1=\delta_0=2\delta_1$, everything works comfortably within the constraints.

There is no necessary relationship between δ_2 and the other response periods; e.g., the motor units can operate with a much higher frequency of pulses than the rest of the sensory-motor network, e.g., with hundreds of muscle-like contractions for each modulation period λ.

The sensory-motor network in Figure 27 is a two-dimensional system. For a three-dimensional system, use two independent two-dimensional systems working at right angles. The essential functionality is the same.

11. Can the behavior of timing device networks be emulated by computer?

Some features of timing devices and networks of timing devices are like those used in computers: the systems are determinate and a cycle of conditions in a timing device is constituted by transitions between steady forms of activity (see section 1). But there are distinctions also. As also discussed in section 1, each timing device has its own response clock that governs transitions between conditions. When timing devices are assembled and some timing devices are subject to sensory modulation, there is no necessary synchronization between transitions in different timing devices. I am not a computer scientist but, in light of these distinctions and operational features, I suggest that there are timing device networks where the behavior cannot be emulated by computational systems.

The following networks have been designed to demonstrate the reasoning behind the suggestion. There are three designs where activity is progressively detached from synchronized control.

In the sensory multiplier assembly shown in Figure 28, all the timing devices have a common response period, δ_0 and a shorter refractory period. A single pulse circulates in the feedback ring (section 3), establishing a regular cycle period of $16\delta_0$. The upper "dependent" part of the assembly contains one-pulse trigger timing devices and two-pulse trigger timing devices (A, B, C, D, E) that are governed by the rousal period $\xi=0.1\delta_0$ (section 5). If there is no sensation at the sensor timing device σ (section 6), pulses onto the two-pulse trigger devices from the feedback ring are synchronized with pulses produced in the dependent system. As a result, pulses are directed onto the collector timing device Γ (a one-pulse trigger timing device), producing output shown in Figure 29.a, "pulse bundles" with a period between pulses of 2.0δ. The sensor timing device σ has a response period $\delta(\sigma)$ that is subject to continuous modulation (Figure 15) according to the strength of the sensation. The maximum response period, δ_M, is $1.3\delta_0$. If there is a sensation with sufficient strength that $\delta(\sigma)>1.1\delta_0$, the pulse from σ onto timing device B will be more than $0.1\delta_0$ later than the pulse from the feedback ring. Then timing device B will not be triggered; nor will any of C, D or E be triggered. If the sensation varies, the result may be like that shown in Figure 29.b. In sum, when $\delta(\sigma)<1.1\delta_0$, there are five pulses in a cycle; when $\delta(\sigma)>1.1\delta_0$, there is one pulse in a cycle.

Figure 28: sensory multiplier, common δ_0

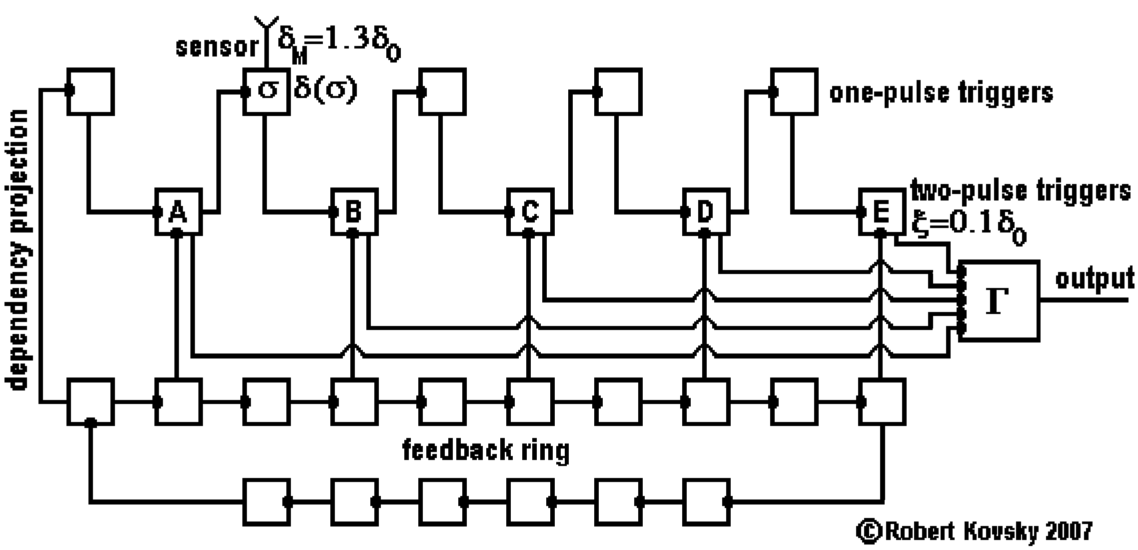
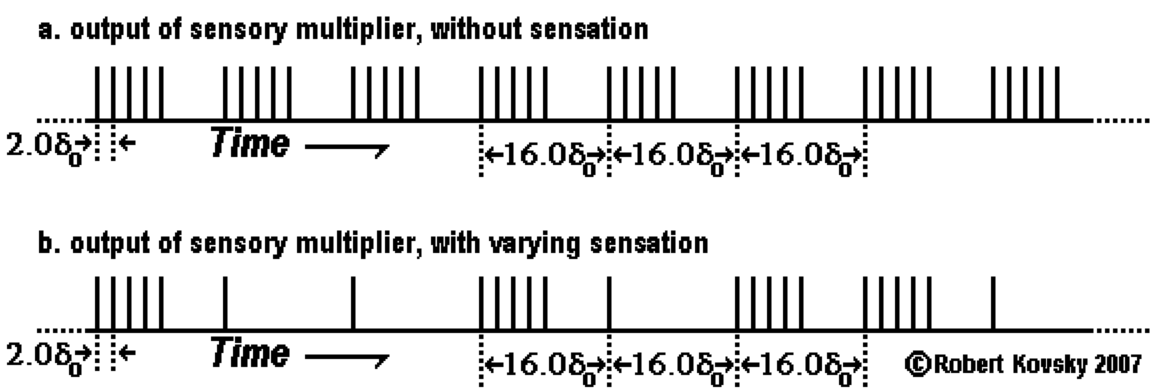


Figure 29: output of sensory multiplier



In the sensory accumulator in Figure 30, there are five sensory units and the rousal period in the two-pulse trigger timing devices is increased to $2.0\delta_0$ so that variations in output will be visible in Figure 31. The output is cyclical overall with period $16\delta_0$ but with various numbers of pulses and internal timing variations. The activity wave (section 2) in the upper dependent part of the assembly passes through the string made up of timing devices A, σ_1, B, σ_2, C, σ_3, D, σ_4 and E. At A, B, C, D and E, a pulse from the upper activity wave is matched against a pulse from the feedback ring; if there is a discrepancy greater than $2.0\delta_0$, the upper activity wave will be interrupted. Each sensor timing device (σ_1, σ_2, σ_3, and σ_4) can add a delay to the upper activity wave, ranging from 0 to $2.2\delta_0$ ($1.0\delta_0 \leq \delta(\sigma_i) \leq 3.2\delta_0$) and the delays accumulate. If $\delta(\sigma_1)>3.0\delta0$, the upper pulse wave will be interrupted and the output will have only a single pulse, as shown in the one-pulse pulse bundle b_2. Pulse bundle b_1 has a long delay ($1.8\delta_0$) at σ_1 ($\delta(\sigma_1)=2.8\delta_0$), but there are no delays thereafter, so the pulse bundle has 5 pulses. If $\delta(\sigma_1)+\delta(\sigma_2)<4.0\delta_0$ but $\delta(\sigma_1)+\delta(\sigma_2)+\delta(\sigma_3)>5.0\delta_0$, the output will have two pulses, as in pulse bundle b_7. If $\delta(\sigma_1)+\delta(\sigma_2)+\delta(\sigma_3)<5.0\delta_0$ but $\delta(\sigma_1)+\delta(\sigma_2)+\delta(\sigma_3)+\delta(\sigma_4)>6.0\delta_0$, there will be four pulses, as in pulse bundles b_4 and b_5. Pulse bundles b_3, b_4, b_5 and b_6 show the effect of increasing sensation that is uniform across the sensors. Pulse bundle b_3 has no delay(= no sensation). A uniform sensation increases the spacing and decreases the number of pulses in pulse bundle b_4. A further increase of sensation increases the spacing to that shown in b_5 but does not change the number of pulses. An additional, equal increase in sensation both increases the spacing and decreases the number of pulses to that shown in b_6: this is a phase change.

Figure 30: sensory accumulator, common δ_0

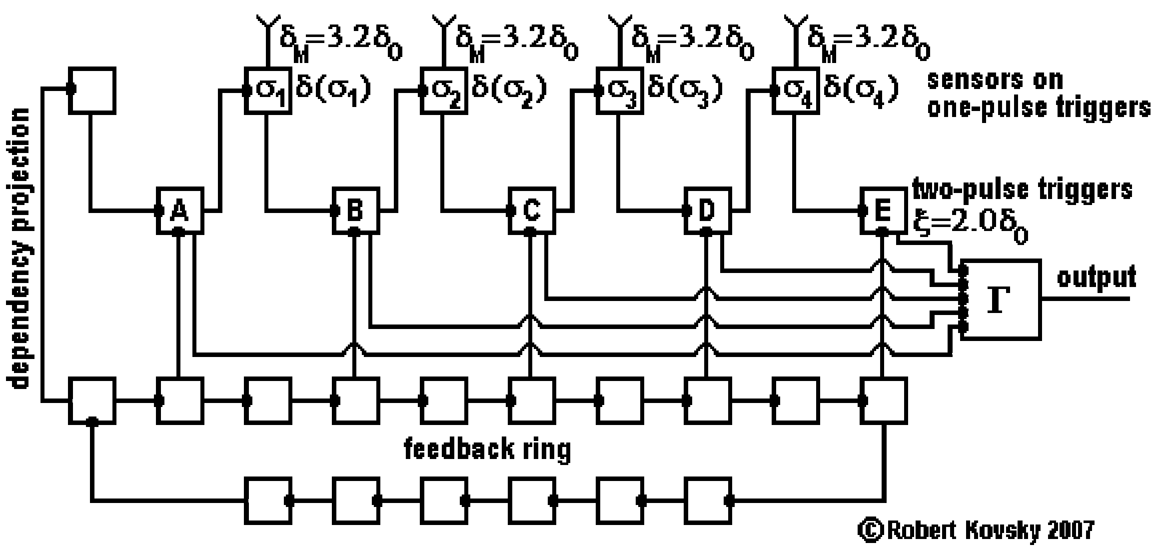
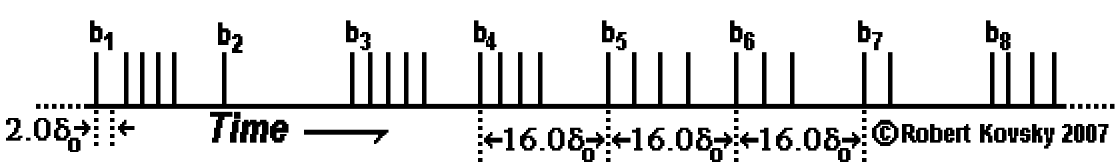


Figure 31: output of sensory accumulator



The comparative sensory accumulator in Figure 32 has two branches of sensors. The feedback ring maintains the underlying cycle period of $16.0\delta_0$ as shown in Figure 33. Activity is otherwise detached from the regular clock-tick of the feedback ring. Pulses from two sensors in different branches are directed onto the two-pulse trigger timing devices and these must arrive in temporal proximity to each other (according to the rousal period, $\xi=0.1\delta_0$) for a pulse to be produced at the output. Pulse bundle b_1 shows output when there is no sensation; two pulses arrive simultaneously at all the two-pulse trigger timing devices generating output pulses every $1.0\delta_0$ within a pulse bundle. If there is sensation at a sensor, the pulse from that sensor is delayed and delays accumulate in each branch. In contrast to previous designs, there is never any interruption of the activity wave in the sensor branches. If, for example, the accumulated delay after sensor σ_3 is more than $0.1\delta_0$ greater than that after sensor σ_7, no pulse will be generated at the two-pulse trigger timing device labeled 3,7; but if, thereafter, the delay at σ_8 is the right amount greater than that at σ_4, so as to balance the delays, a pulse will be generated at the two-pulse trigger timing device labeled 4,8; see pulse bundle b_2. The temporal spread between pulses in a pulse bundle can be as great as $3.2\delta_0$ (pulse bundle b_3). There is never any delay of either pulse onto the two-pulse trigger timing device labeled A and timing device A always produces a pulse, initiating a pulse bundle with regular periodicity.

Figure 32: comparative sensory accumulator, common δ_0

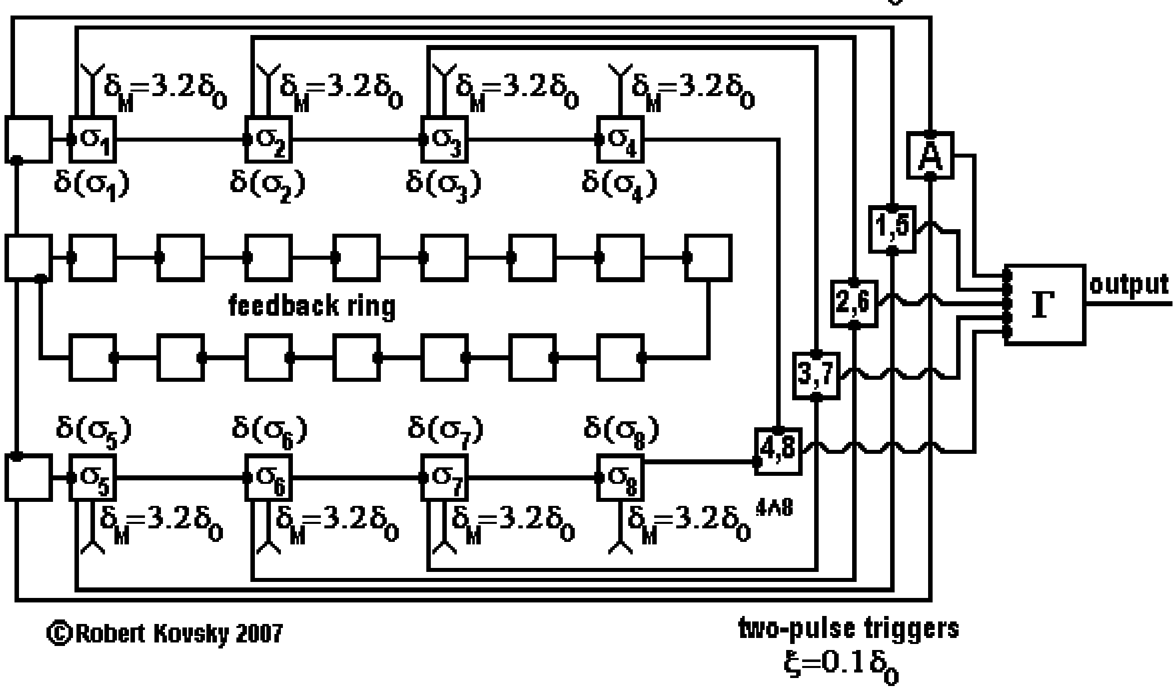
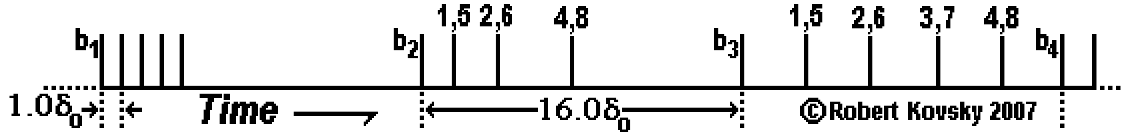


Figure 33: output of comparative sensory accumulator



The comparative sensory accumulator supports the suggestion set forth at the beginning of this section, namely, that there are timing device assemblies where the activity cannot be emulated by computer. A computer emulation would require something like the pulse progress charts shown in Figures 2, 4, 5, etc. To attempt emulation, the status of sensors could be monitored at regular intervals. The problem comes when one attempts to choose the size of the regular intervals. If sensations are varying unpredictably, there is no way to predict when to monitor the sensors. Hence, the regular monitoring intervals must shrink to an infinitesimal size and the number needed must increase indefinitely, that is, toward infinity. For example, the output pulse labeled 4,8 in pulse bundle b_2 in Figure 33 occurs because of a near-equality of accumulated delays in the two branches. The result depends both on exactly when a trigger pulse arrives at sensor σ_4 and also the sensation at that sensor at that moment; and, again, a similar but different instant of arrival of a pulse at sensor σ_8. Unlike previous pulse progress charts, the activity here is unpredictable. To follow the activities of the timing devices and construct a digitalized computer emulation, it would be necessary to update the pulse progress chart every instant.

The underlying operational feature responsible for this state of affairs is what I call ***phase changes***, namely, that activities of timing device assemblies change discontinuously when timing intervals undergo changes as to approach 0. The slightest mismatch could result in an error that affects an entire pulse.

One might consider that an inability to emulate activities of timing device assemblies would disappear if operations were real rather than ideal, i.e., if there is a sizeable duration of a pulse rather an instantaneous pulse or if transitions between conditions (section 1) occurred over a sizeable duration of time. But these changes would not, in my view, change the argument. Rather, the argument is based on the existence of phase changes and phase changes will occur even if the durations of pulses and/or transitions between conditions were sizeable. Either a pulse occurs or it doesn't and there is no way to "smooth" out the pulse or to contrive a partway pulse production. Such phase changes occur at every level of timing device operations, from the single timing device up through the largest-scale assemblies and networks. Such phase changes, in my view, model the activities of animals and humans where a tiny change in an influence — a slight increase of an odor signifying danger or a single changed word in a conversation — can quickly result in a large-scale change in behavior of the entire organism.