Wriggler I, an engineered organism

Initial project: constructing repertoires of movement that shift between stationary balancing positions and resemble mathematical forms

In anticipated operations, Wriggler I moves on the bottom of a water-filled tank, such as an aquarium.

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planned repertoires of movement:

1. aversion movements on contact
2. self-touching movements
3. wavy locomotion movements
4. gaited locomotion movements
5. stationary positions maintained by equal and opposing twitches ("balancing positions")
6. movements that start and end at balancing positions

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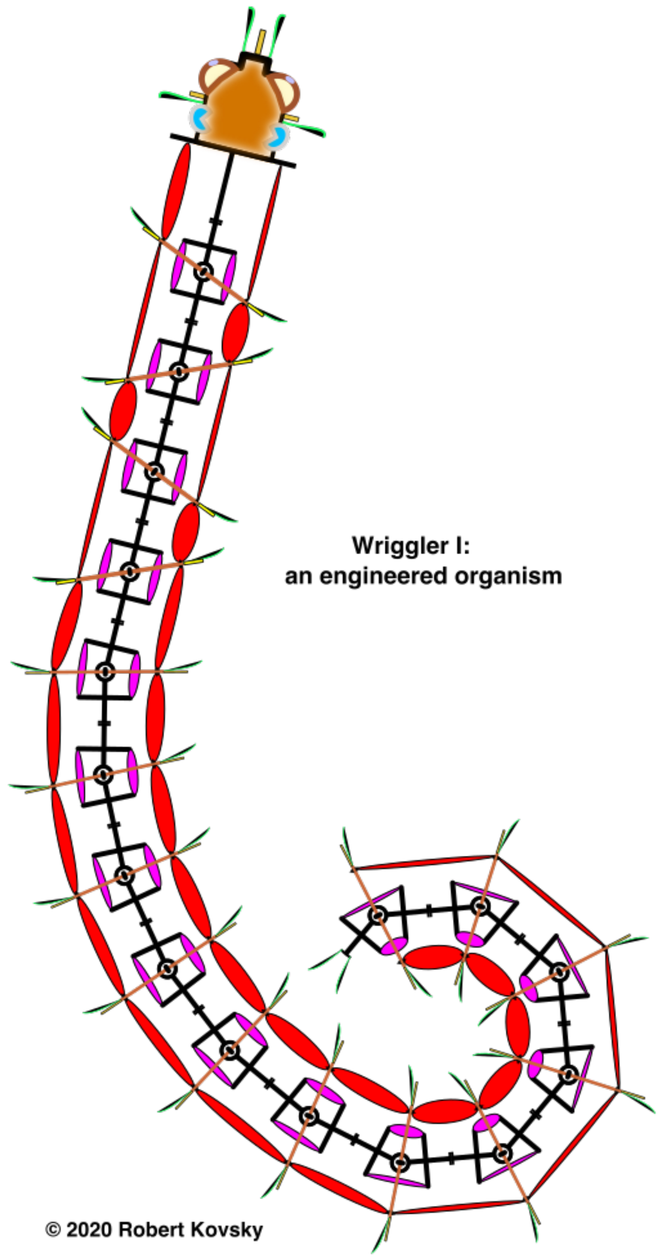
influences and controls:

1. contact detectors
2. water current detectors
3. mover (muscle) length detectors
4. internal stress detectors
5. angle detectors in joints
6. visible objects
7. commands in forms of audible tones and harmonic intervals

In the adjacent image of Wriggler I, the organism is moving out of a coiled self-touching position and is producing (from head to tail) gaited locomotion movements, wavy locomotion movements and stationary balancing positions.



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Introduction: a rational kind of movement.

"Many material bodies that differ in their dynamics share a common statics."
C. Truesdell, *Rational Thermodynamics*, 2d ed. at 24.

Long-range goals of the project include engineered organisms (wrigglers) that move like animals. Like movements of a foraging animal in a risky environment, movements of fully-developed wrigglers will be selected from complex repertoires, with sensitivity to transient conditions and to objects touched or located visually.

Wriggler 1 aims to function as an imitation worm made of electronics devices and plastic parts that moves on the bottom of a tank of water similar to a home aquarium. Movements are two-dimensional, in a plane. Anticipated developments include wrigglers that move in three dimensions.

In some ways wrigglers resemble computerized devices and robots but there are fundamental distinctions. There is no computer or "finite state machine" in a wriggler. Its devices operate according to new "rate-based" Virtual Energy (VE) principles where flows of VE have a character like flows of blood sugar in animal bodies or flows of electricity in electronics devices. Instead of stored bits of data as in computers, storage bodies contain VE. Streams of control codes for conversions of VE and for productions of movement resemble musical scores rather than computer programs. Strengths and timings of movements are controlled by instantaneous ***pulses*** – idealized versions of action potentials in animal nerves. Each pulse carries one unit of VE, called a "bang" and denoted by !.

The project aims to develop engineered organisms that combine multiple repertoires of movements while performing exercises of freedom. Exercises of freedom embody a physical principle of freedom called Shimmering Sensitivity that I suggest can operate in networks of quadnet devices during a critical moment — when many possible movements change into selected actual movements. It's like choosing a candy bar from a rack of snacks in a store.

As a means of building towards long-range goals, Part II of this project develops designs for production of a limited rational repertoire that is made of stationary positions and shifting movements between stationary positions. A period of rest separates successive movements, which are thus detached from each other. A rational repertoire of detached shifting movements can be constructed both for engineered organisms built from VE devices and also for computerized systems and robots — applying, at least metaphorically, the epigram of Truesdell, above.

All designs are imaginary and no working models are foreseeable at this time.

B. Anticipated movements of Wriggler I.

1. Fundamental movements are produced by the whole organism.

The design for Wriggler I introduces features that are intended for incorporation in successor projects and that involve the whole organism.

Of first importance is sustained readiness for production of multiple possible movements by means of continuous streaming of Virtual Energy through muscle-like devices called “movers” and through devices that aim to model neurons (“bursters”) and groups of neurons (“quadnets”). Principles of readiness and multiplicity appear on several scales and in many aspects of the construction, including multiple modes of operation of individual bursters, multiple kinds of connectors in collective quadnet devices and multiple repertoires of the whole organism. Balancing positions are maintained by opposing twitches that can continue in a steady way – or that can go through slow changes – or that can go through big sudden changes. In anticipated developments, a moving body (e.g., like that of a bird in flight) produces repetitive cycles that include whole-body choices as to bodily orientation, stroke forces and direction of movement.

Other whole-body features arise from the repetitive structure of Wriggler I’s spine, with 16 identical joints and brachia (limbs). All animal bodies are constituted by structures of repetitive units that have collective functioning, including cell membranes made of repeating molecules, DNA, branching networks, whole organs – and the principle extends to societies of bees, fish, birds and human beings. The number 16 is convenient but not essential. Examples in this project use a simple spinal assembly with 8 joints. Structures can be extended to a large number of joints, e.g., to a model of an eel.

Designs combine forms in space and forms in time. Wriggler I incorporates geometrical forms such as squares, triangles and trapezoids, which simplify constructions and analysis. Pulsational operations of VE devices incorporate forms in time that resemble those of music. In wrigglers, spatial forms and temporal forms are each subject to variations and combinations; and changes in the two kinds of forms can be unified and extend over the whole organism.

Repertoires of full-range whole-body movements are foundational subject matters of construction. Specific kinds of movement are constructed on top of foundations by restricting ranges of motion and imposing constraints (see §§ II.B.3 and II.F.3).

2. Multiple kinds of movement co-exist in the organism.

Wriggler I incorporates two distinct control systems that share movers and have variable relationships. The two systems can operate independently; or they can combine and coordinate operations; or one may seize control from the other.

One system's control devices are located next to spinal joints, with interconnected repetitive modules along the spine; this system ***resides*** near the joints and produces ***residential movements***. The other system's control devices are located in the head of the organism and produce ***remotely-controlled movements***.

Residential movements, e.g., aversion movements and wavy locomotion movements, depend directly on detectors located in and on the body — responding to external contacts, flows of water, mover lengths, internal stresses and angles of joints. Networks of such detectors, called the ***sensorium***, pervade the body of the organism and interact with movers through the residential control system.

In the other case, signals for remotely-controlled movements are generated in a ***scriptorium*** that operates in the head. Signals for movements are "pre-loaded" prior to the time of production, as in the scripted balancing positions and detached shifting movements that are constructed in Part II of this project.

Contrasting the two control systems: Residential operations are highly variable and interact in complex ways with the body and the environment during actual production of movements. Remote operations produce a great many movements and follow scripted plans – but, at least at this time, changes of remote movements are limited during actual production to halting, revising or reversing a script.

Categorical terms "residential" and "remote" for two kinds of movement were similarly used by William James in *The Principles of Psychology* in connection with animals and human beings. Reflexes are residential movements in animals and are modeled by aversion movements in wrigglers. Biological residential movements include wave-like swimming in worms and fish, where movements are passed along the body, from head to tail.

Animals and people touch, preen and scratch their own bodies. In laboratory research on frogs, complex self-touching movements occur after severing the brain. (James at 9 ("conscious intelligence in the frog's spinal cord") and Chap. 2; Mark L. Latash, *Fundamentals of Motor Control* at 8-9, 181-183.) It appears that such movements are produced in a spinal network of neuronal groups in vertebrae and adjacent dorsal root ganglia. I suggest that, as part of a scratching movement, a feeling of an itch is generated as a result of operations in such groups. (In my approach, additional layers of an itchy feeling can be generated in human beings in the cerebellum and cerebrum, which have independent means of control.)

In cyclical residential movements – swimming movements of fish or ordinary walking of a person – material properties (e.g., masses, viscosity, elasticity) bind together timings and strengths of movements. In other words, a change in the rate of production of a cyclical residential movement usually involves a change in strength, with more strength required for faster production. Likewise, an ordinary person can walk slower and softer than the usual rate but not faster and softer. (To walk faster and softer — with minimal foot impact — requires a lot of muscular skill and practice.)

In remotely-controlled movements, on the other hand, strengths and timings may be detachable: movements can be isolated and sequenced independently of each other. Such movements include shooting a basketball from the foul line or tossing a wad of paper into a wastebasket, where the strength of the toss is first "set" and then activated after a variable pause that may depend on a bodily feeling of readiness. Keyboards of musical instruments and computers provide other places where variable residential movements follow detachable remote selections.

"Standing and waiting" involves postural reflexes and residential movements; starting off in a particular direction is the result of a remote command. The remote system, which has been "waiting," seizes control from the residential system to start the movement. (See Latash at 57-58 as to the "posture-movement paradox.")

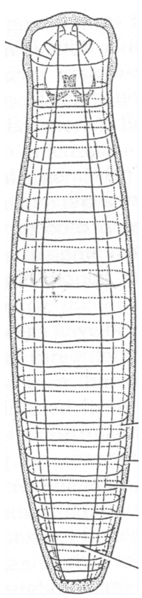
Engineers use terms "feedback" and "feed forward" to denote a distinction like the residential/remote distinction. (Latash at 114 *et. seq.*; John Hertz, Anders Krogh & Richard Palmer, *Introduction to the Theory of Neural Computation* at 90 *et. seq.*)

a. Residential movements of the organism are based in the sensorium – a network of detectors in the body.

(i) ***Aversion movements*** are triggered by signals from contact detectors (whiskers") that bend when they meet an external object: in response, the spine of the organism pulls back in a curve, moving away from the point or area of contact. The extent of an aversion movement may vary in a range from incremental to a maximum. Maximum aversion movements express extremes of force and suddenness for Wriggler I and are of definitional importance.

Incremental aversion movements may brush an object with whiskers. Aversion movements can be combined with wavy locomotion movements, which are also residential movements. The combination aims to resemble an aquatic worm that curves around and brushes an obstruction while continuing to move in a direct line.

(ii) In ***self-touching movements***, curves are tightened until one contact detector touches another contact detector; both detectors bend and their signals interact. The design of Wriggler I allows for self-touching of every contact detector with at least one other detector.



Self-touching movements and aversion movements are responsive to signals generated in the ***sensorium*** that pervades the body of the organism. An anticipated sensorium incorporates networks of detectors of various influences and interfaces with residential burster modules that drive movers.

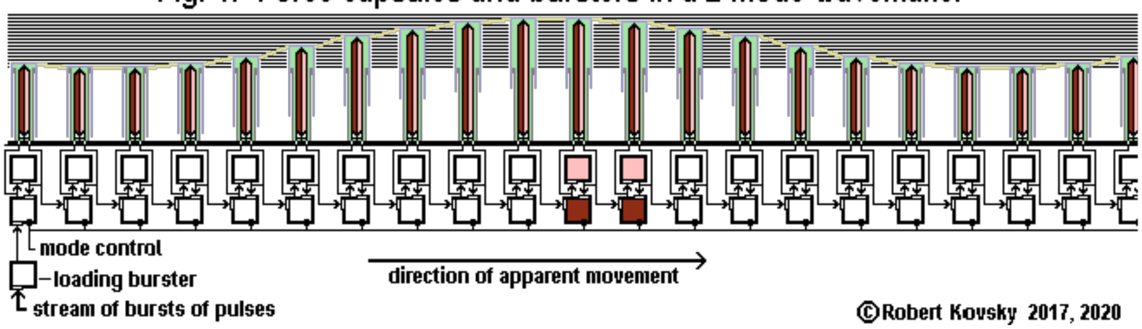
The adjacent image shows the "ladder-like nervous system of the rhabdocoel *Bothrioplana*," a flatworm. [Illustration and description from Brusca, Brusca and Haver, *Invertebrates* (1990) at 295.]

The flatworm's nervous system resembles a cylindrical quadnet device (CQN). In anticipated wriggler designs, an initial sensorial CQN with a module at each intersection operates as an interface between contact detectors and spinal and brachial movers. Further development would incorporate sensorial signals based in water flows, lengths of movers, internal stresses and angular bends.

During certain anticipated operations, the whole body and sensorium of the organism participate in selections and productions of movement. This goal of development was described by William James in *The Principles of Psychology*, "The Production of Movement," where he concluded that ***feelings*** are foundational, "that every possible feeling produces a movement, and that the movement is a movement of the entire organism, and of each and all of its parts."

(iii) ***Wavy locomotion movements***. In anticipated developments, oscillatory waves travel down the spine of Wriggler I and are coordinated with movements of brachia (limbs) – and perhaps peds (feet or paddles) – to produce locomotion movements. Depending on variable operations, such waves may originate in various ways, e.g., spontaneously ("on their own") in the spine, perhaps triggered by sensorial stimulation or by a changing activation of devices; or they may originate in the head. Regardless of origination, wavy locomotion movements vary in response to variations in signals from sensoria. Precursors include the "wavemaker" shown in Fig. 1 and found in the paradigms project referenced below.

Fig. 1. Force capsules and bursters in a 2-mode wavemaker



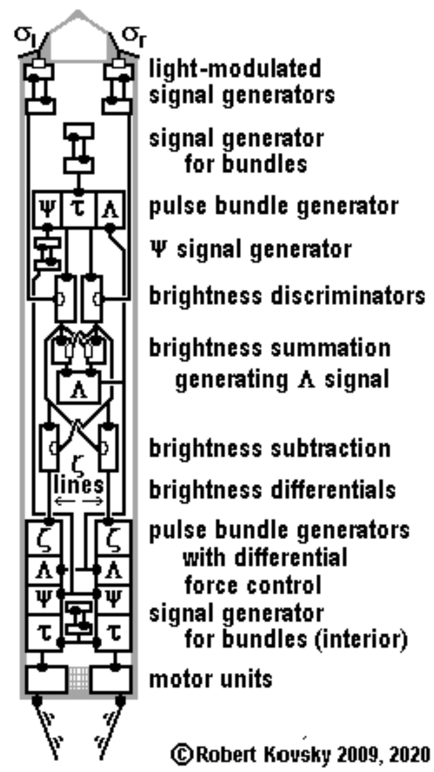
b. Remotely-controlled movements are based in the scriptorium – a command center in the head.

Part II constructs a rudimentary remote command center like that in the head of an engineered organism — a simple scriptorium that drives certain kinds of movements. The scriptorium operates “on its own” prior to anticipated influences based in sight, sound or touch. Sensorial influences are then incorporated in enlarged designs.

In animals, visual influences are detected at the head, distant from influences based in senses of the body. Processing of visual influences starts with operations that are detached from muscles of locomotion. As a result of such independence, the head can position the body so that residential locomotion movements are directed towards an object detected by eyes.

In models, certain goal-directed locomotion movements aim to mimic movements of a predator following prey. A precursor is shown in Fig. 2 found in the harmonics project, showing an engineered organism that follows a light. Signals in the Fig. 2 design were based on "pulse bundles," which are superseded in this project by pulse bursts.

Fig. 2. Light-follower



Another repertoire is ***gaited locomotion movements***, back-and-forth movements produced by a group of spinal and brachial movers with a collective meter and rhythm, e.g., as shown near the head of Wriggler I in the front-page image. Such movements might be produced by signals from the scriptorium based on scripts similar to those constructed in part II. They might also be independently produced in bursters at spinal joints through residential operations that resemble standing waves in physics paradigms (theory of sound). In a mixed mode, movements start according to directions from the head and then the body acquires the movements and maintains them if signals from the head cease.

B. Foundations, constituents and goals of construction.

1. Components are based on precursors.

The anticipated fully-developed Wriggler I incorporates multiple independent Virtual Energy (VE) device systems that also interact with each other:

(1) muscle-like movers attached to the spinal assembly and brachia (limbs);

(2) VE device modules that drive movers and process signals (modules resemble groups of neurons located in and around vertebrae and in brains);

(3) internal detectors of stresses, mover lengths and angles of joints; external detectors that bend in response to contact and that measure a flow of water;

(4) modules resembling eyes with a moving lens that focuses an image on an array of light-sensitive detectors, thus locating objects in the environment;

(5) detectors like ears that identify audible tones and harmonics - so that instructions to an operating organism resemble chords and melodies.

Device systems are based on the following prior projects accessible at quadnets.com/sitemap.html

Approaching Freedom: unified paradigms of choice in psychology, physics and technology (2018): the ***choice project*** articulates long-range goals and current conceptions of Shimmering Sensitivity.

Actual time, detached time and controlled time: physical paradigms and energy foundations (2018 version): the ***paradigms project*** compares, contrasts and combines different kinds of time and energy concepts. Chief VE devices used in this project (pulsers, force devices and bursters) are discussed in detail.

Original designs for force devices and bursters are set forth in the ***bursters project***: Elemental Constructions in Virtual Energy Domains (2015).

How to solve free-will puzzles and overcome limitations of platonic science (2016 version): the ***free-will puzzle project*** investigates movements, feelings and freedom in actual life, e.g., in sports competitions, musical performances and jury trials. A Dogtail for Wagging investigates classes of muscle-like movements.

Timing Devices: a Kit of Parts, the ***timing devices project***, includes An Eye for Sharp Contrast (2011), also discussed in the free-will puzzle project in § 5(a). The related ***harmonics project***, An Ear for Pythagorean Harmonics (2010) (a .pdf file), is part of a constellation of online projects.

Quad Nets: Material Foundations for Thermal Device Models of Brains (2006): the ***quadnets project*** includes primal design principles, the VE functional and discussion of origins of Shimmering Sensitivity in phenomena of materials science.

3. Goals of development include networks of quadnet devices:

Part II of the project constructs a ***spinal driver module*** that drives movements through a discharge port in the scriptorium. Movements follow scripts that are generated and processed by quadnet device operations in the module.

In anticipated developments, Wriggler I will combine multiple systems of muscle-like movement and sensory-like detection. Each system of movement and/or detection incorporates one or more quadnet interfaces for output and/or input.

A quadnet device contains many uniform elemental devices (or modules) that have both independent and collective operations. It connects to other quadnet devices in a network of interfaces. In anticipated developments, quadnets participate in transient assemblies and momentary operations that can be independent, synchronous and/or wavy. Multiple systems of movement and detection interact; movements are selected from rich repertoires and with sensitivity to tiny influences.

a. **Scripts directing movements from the scriptorium.** Constructed in part II, the spinal driver module generates and processes scripts that produce movements. In anticipated developments, scriptorial quadnets interface with other modules so that, as outlined below, audible harmonic sequences command scripted movements, which interact with sensorial signals from the body and maps of visual objects.

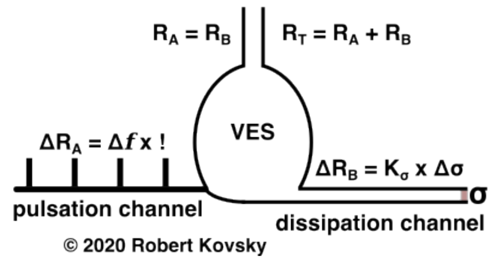
b. **Mover-sensor interactions in the sensorium.** A primal sensorial signal is a series of pulses, a ***pulse train***, with a fixed or slowly varying period between pulses. Pulse trains resemble musical tones and are used in various device designs.

A detector in the sensorium responds to a variable influence by changing its period of pulsation. A pulser design is shown in Fig. 3. Faster pulses mean a larger bend in a whisker, a bigger mover contraction, a faster water flow or a stronger stress.

In the Fig. 3 design, a Virtual Energy Store (VES) fuels a dissipation channel and a pulsation channel with equal flows of VE; a variable rate of total VE inflow R_T maintains a homeostatic (constant level) of VE in the VES.

Linear forms are sufficient to sketch the design. In the dissipation channel, an increased sensory influence $\Delta\sigma$ causes increased VE flow ΔR_B, with a proportionality factor K_σ. R_T increases to supply ΔR_B. Operating constraint $R_A = R_B$ causes an equal increase of VE flow ΔR_A in the pulsation channel, resulting in faster discharges.

Fig. 3. Pulser for sensorial detection



Discharges in the pulsation channel produce pulses that each carry a quantity of VE of 1 bang (unit of VE) or 1! and with a frequency ***f***. Hence, $\Delta f = (K_\sigma/!) \times \Delta\sigma$.

c. **Copies of the sensorium in the scriptorium (body-maps).** Secondary projections from sensorial detectors carry signals to the scriptorium, where they are reconstituted in quadnets that map aspects of the body. Interactions between scripting quadnets and body-map quadnets can control movements, e.g., when scripts are modified to direct movements away from stimuli defined by sensorial detections and to adjust movements in response to signals in a body-map.

d. **Visual maps of bright and dark objects in exterior space.** Opposing mover designs in part II can be adapted to position a lens that focuses light on an array of light detectors. Visible space is thus divided into radial slots that are indexed by drive signals for movers. The base of a radial slot contains detectors that measure the brightness of and distance to a visual object, developing designs from the timing device project An Eye for Sharp Contrast. Radial slot index, distance and brightness are organized in quadnet interfaces. An anticipated interaction produces movements that position the head and body of Wriggler I in a direct line aimed at a bright object that is visually mapped.

e. **Processing harmonic sequences.** Timing devices generate and process signals called pulse trains, that resemble tones in music. As with musical tones, two pulse trains can be related by harmonic intervals called: fundamental (or unison), octave, fifth, fourth, major and minor thirds and major and minor sixths. Harmonic intervals and their durations can be used as elements of a language.

In anticipated wriggler projects, two-tone intervals are organized in sequences, which resemble sequences of chords . Perhaps one tone in the chord sustains the fundamental tone during the sequence while the other tone varies. The harmonies and changes are tracked by devices and interpreted to produce movements.

In scripts constructed in part II, “the researcher” intervenes to trigger certain operations; this could be done with a whistle. The seeds in a script might be specified by a sequence of harmonic intervals that are similar to a melody.

In another anticipated application, the 8-place configuration vector **p** in part II constructions is adapted to represent musical timbre in a way similar to that of a tone synthesizer. The first position in the vector specifies the strength of the fundamental; the second position in the vector specifies the strength of the octave; the third position, the strength of the fifth harmonic; and so on for fourths, thirds and sixths. Each distinct vector corresponds to a particular timbre. Invented classes of devices can generate and detect timbres as well as harmonies. A group of identical wrigglers could communicate with each other and coordinate movements using such a musical language of harmonies and timbres.

4. Adaptations of scientific forms

Developing VE designs draw on standard paradigms of materials science, engineering and physics.

a. **Phase changes in general; critical point phase changes in magnets; mathematical Ising model.** Phase changes are whole-body transformations of physical materials and material bodies. Natural examples include liquid water evaporating into steam or freezing into ice. Phase changes in liquid crystals occur naturally and have many engineering applications, including critical point phase changes, which also occur in magnets that lose and regain their magnetism on heating and cooling. Phase changes involved in snowflakes and magnets are explored in prior projects (especially the choice project and the free-will puzzles project). The mathematical Ising model of critical-point phase changes in magnets was a precursor for quadnet devices.

b. **Normal modes of small oscillations in arrays of identical particles; theory of sound; crystal lattices and diffraction; dual spaces.** Standard paradigms posit arrays of identical particles or molecules with an elastic interaction in which normal modes organize classes of small oscillations. If movers in a VE spinal assembly are replaced by rubber bands, small movements around midline positions of the two versions are comparable. The rubber band version is subject to methods of theory of sound, virtual forces and calculus of variations. Such methods are also applied to crystal lattices that model metals such as iron and aluminum. Metallic crystal lattices that go through phase changes were another precursor for quadnet devices. Dual spaces relate crystal lattices to diffraction patterns generated by x-rays and electron beams passing through the lattices. Similar methods and dual spaces based in quadnet device operations suggest possible avenues for developing processes of imagery and memory.

c. **Electromagnetism, electrical and electronics networks.** VE designs in this project appear to be suitable for embodiment in devices that resemble current products of electronics industries. The Kit of Parts method resembles methods of electrical and electronics hobbyists. Faraday's law of induction is suggestive of possible avenues for developing processes of imagery and memory. A precursor project, Technology of Freedom (1998), was chiefly electrical, with methods that have similarities to those of neural computation. The timing devices project An Eye for Sharp Contrast adapted methods of electrical relays (e.g., in Level Shifter).

5. Methods of Virtual Energy and Kits of Parts

In my approach, an Energy principle is a human invention that enables us to describe and control certain kinds of processes in certain classes of material bodies. Such bodies and processes make up the ***domain of application*** of the Energy principle. A domain of application can be extended by further inventions.

I presume that, as to any particular Energy principle, classes of applications in its extended domain are limited; many processes in many bodies are **not** described or controlled by that Energy principle. As a guard against excessive belief in human inventions, I presume that important processes in animal bodies (e.g., meiosis) can never be satisfactorily described by any such Energy principle. I presume that an "actual energy" passes through animal bodies and generates feelings — and I also presume that, at this time, we are not able to describe it sufficiently for applications.

Different Energy principles are used in thermodynamics, statistical mechanics and kinetic theory. Some simple applications are described and controlled by multiple Energy principles, e.g., dilute hot gases and phase equilibria. Other applications are in specific domains defined by, e.g., Helmholtz free energy, Onsager's reciprocity relations, the Maxwell-Boltzmann equation and Hopfield's energy function. (See Truesdell at 69, 71-72, 155, 424; Hertz *et. al.* at 21 *et. seq.*)

In scientific approaches, in contrast, energy is presumed to be inherent in bodies and subject to universal laws of nature. It is said that energy can be neither created nor lost and that the summed amount of energy in the universe is constant. In a scientific approach, the universe is a perfect, eternal storage body for energy, whatever the movements and conversions of such energy.

My approach is consistent with observed facts that an appearance of Conserved Energy in one place requires substantial dissipations elsewhere. Energy is never fully conserved but some energy is always being dissipated by radiation into the sky. Such facts suggest that energy radiating from the Sun will ultimately vanish into empty space, perhaps after a stay on Earth or other bodies. Perhaps a concept of Vanishing Energy might provide alternative or additional explanations for "the red-shift of starlight" and "the arrow of time."

In my view, only limited classes of processes in certain bodies are within extended domains of application of Conserved Energy principles; and important processes in living animal bodies are **not** within such domains. In particular, there are serious shortcomings in descriptions of biological processes in terms of Conserved Energy. Researchers can specify energy ***states*** in biochemical processes; but models for ***rates*** are limited, complex and adjusted to fit the evidence. States in biochemical processes are fixed and provide clear points of reference. Rates of processes vary widely and depend on many influences.

Limitations of Conserved Energy are rooted in its temporal character. In the central domain of application of Conserved Energy are bodies described by ***equilibrium states*** and ***equations of state***; restricted processes are ***quasi-static***.

An equilibrium state does not change unless and until an external influence causes change. An equation of state (e.g., pV=RT for the Ideal Gas) specifies the possible equilibrium states of the body. In a quasi-static process, a body that starts in an equilibrium state is subjected to a series of changes in external influences that cause changes in the body; but each change is small and the body returns to an equilibrium state after each small change.

Conserved Energy principles can be extended beyond their central domain of application to include certain kinds of forceful movements; but extensions remain tethered to central limitations and restrictions and to the uniformities they engender. Slowing or quickening the speed of a quasi-static process leaves results unchanged, like a movie film run at a slower or faster speed. Conserved Energy principles would even allow the film to run backwards, with movements reversed.

In contrast, results often change in happenstance ways when an animal body moves faster. A movement usually safe (e.g., slicing vegetables) may become injurious when performed hastily; and an injury cannot be reversed, although it may heal.

Unlike bodies in the central domain of Conserved Energy applications, animal bodies are always changing and are never in an equilibrium state. A sleeping animal wakes up and spontaneously starts to satisfy bodily needs.

No equation of state describes movements of one-celled animals like amebae and paramecia; such movements appear to be beyond scientific explanation. (Brusca, 50-53 150-152.) Likewise, spontaneous movements of a person dancing at a party cannot be described by a quasi-static process. Neither can the aggressive, targeted “lashing out” of an animal that has suffered an attack by another animal.

Other differences can be noted by comparing movements of air-borne drones to movements of birds in flight. Movements in air are simpler than those on land or in water, whatever the energy sources and conversions that provide lift, propulsion and steering. Movements of drones follow trajectories that are chosen by human controllers and that are sustained by continuously available power.

In contrast, the flight of a bird is powered by momentary flaps of wings. Each flap is a distinct event with many possible variations produced by numerous muscles operating on different body parts with different strengths from different angles; each flap is selected during the event in ways that seem to be beyond calculation, e.g., in order to maintain the bird’s position inside a turning flock. Movements of birds are immediately responsive to environmental changes such as a gunshot, while movements of drones may have to await remote control.

Virtual Energy (VE) has been developed for closer modeling of movements of animals and to provide a basis for Shimmering Sensitivity in modeling exercises of freedom by animal bodies. (Conserved Energy principles lead to "determinism," which excludes freedom.)

VE shares important features with Conserved Energy. Just like with the classic formulations of Conserved Energy, inflows of VE depend on external sources and there is no new energy that appears during any process. In both kinds of processes, energy is irreversibly lost when it is dissipated as heat or radiation.

A chief distinction between Virtual Energy and Conserved Energy is that VE is a flow or rate while Conserved Energy is defined by states. Conserved Energy is like water in a lake, with the source far from the mouth; Virtual Energy is like water in a stream with variable speeds and flows. Shimmering Sensitivity is like turbulence in water that requires a high rate of flow.

Additionally, Virtual Energy is an ambiguous concept that is modified to fit a variety of applications. Ambiguity in VE leads to parallels with Conserved Energy in certain applications. ***Stationary balancing positions*** constructed in part II resemble equilibrium states in Conserved Energy domains. Detached shifting movements between stationary balancing positions, represented by ***scripts***, resemble quasi-static processes. The organizational math-like form for VE devices is the ***Virtual Energy (VE) functional*** instead of an equation of state. The VE functional adapts the Internal Energy principle of Conserved Energy, invented by Rudolf Clausius (1822-1888); here, similar operating principles revolve around the ***Virtual Energy Store*** (or **VES**).

Clausius' Internal Energy **U** began as a mathematical form applicable to steam (phenomena of heat, work, phase equilibria). It developed into a versatile converter between multiple forms of energy: thus, heat, work, mechanical stress, electrical tension, magnetism and energies in chemical bonds can be changed into each other via Internal Energy, according to measurable proportions and with certain losses or dissipations. E.g.: put heat into the Internal Energy of steam as its temperature rises; take out work as its temperature falls.

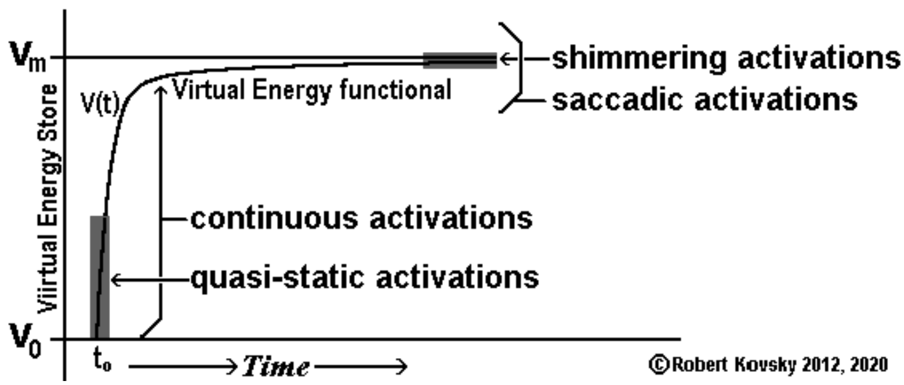
For lossless conversions, the foregoing changes are denoted:

$dU = (T \times dS) - (p \times dV) + (J \times dL) + (V \times dQ) + (H \times dM) + \Sigma(\mu_i \times dn_i)$.

Similarly, in a VE device, a flow of VE from a source arrives at a device at a rate denoted by "R." The VE device converts source VE into stored VE in a Virtual Energy Store (VES); and then it converts stored VE into forceful twitches or pulse discharges. Pulses also carry VE — in some devices, VE in arriving pulses is combined with source VE stored in the VES to control device operations.

The Virtual Energy functional is shown in Fig. 4. The general equation is $V(t) = V_0 + [(R/D) \times (1 - \exp(-D(t - t_0))]$. V(t) specifies the momentary level of VE in the VES, with limits V_0 and $V_m = V_0 + R/D$. In the simplest application, t_0 is the instant of the most recent discharge; R is the fixed rate of inflow of VE. D is a co-efficient factor for dissipation inside the VES and multiples the difference between V(t) and V_0. A higher value of V(t) produces more dissipation.

Fig. 4. Levels of Activation Organized by the Virtual Energy functional



A "functional" is a mathematical form that generates classes of functions when certain values are specified. Here, specifications identify ***regions*** of the functional that control VE device operations. In other words, device operations involve specific parts of the functional labeled in Fig. 4 as ***activations***. An activation is a domain of a ***kit of parts***. Kits of pulsers, bursters, movers, timing devices and quadnets operate in regions of the VE functional. Parts in a kit share foundational operating principles and also allow for additional principles and new inventions.

Quasi-static and ***continuous*** "low-level" operations are partially conformable to principles of Conserved Energy, as shown in part II for bursters. Pulsers operate with a quasi-static activation; the trace of the VE functional closely resembles a linear form. Continuous operations of movers are similar to those of bursters.

In contrast, timing devices operate with "high-level" ***saccadic*** activations. The primal timing device hovers with V(t) near the asymptotic level (V_m) where VE dissipation is about equal to R — until VE in an arriving pulse combines with VE in the VES and triggers discharge of pulses directed at other timing devices that are ready to be triggered. Variable periods of time called ***timing intervals*** control timing device operations. Anticipated shimmering operations involve collective discharges of quadnet devices and require the highest activations.

Some VE methods are comparable to scientific methods, e.g., as formulated and applied by Truesdell to construct a version of classical thermodynamic (63-68).

“Any branch of mathematical physics is constructed in terms of: (1) a list of *primitive quantities*,” mathematically defined; “(2) *Definitions* of other quantities in terms of the primitives; (3) *General axioms* stated as mathematical relations satisfied by the primitives and the defined quantities; (4) Proved *theorems*…”

Primitive quantities in Truesdell’s construction include a simple body, certain material properties of the body and its temperature. General axioms are called “*general principles* or *physical laws*: They refer to all systems covered by the theory.” The ***first axiom*** is an energy balance equation (“often called ‘the first law of thermodynamics’ ”) stating that “the rate of increase of *internal energy*” of the body exactly divides into two forms, called ***heating*** and ***working***. “Work and energy may always be converted into heat; but each body is limited in the rate at which it can convert heat into energy without doing work. This is the content of the ***second axiom***,” which leads to the “second law of thermodynamics.”

In addition, specific applications are defined by mathematical relations for particular bodies, called ***constitutive axioms*** and ***constitutive relations***, e.g., pV=RT for the Ideal Gas [Classification of a principle as a general axiom or a constitutive axiom may be subject to re-interpretation. See Truesdell 71-72, n.8]

“[T]he choice of primitives, definitions, and axioms is not unique … any given theory may be constructed in infinitely many but equivalent ways.”

Truesdell also constructs a different version of classical thermodynamics (82-106) by means of an imaginary device called the ***Carnot heat engine*** — which is a mathematical model of a steam engine, invented by Sadi Carnot (1796-1832). In the initial condition, such an engine contains a body of steam at a hot temperature. Then, during a ***work stroke***, the body of steam is cooled to a low temperature and work or “motive power” is produced. Different kinds of strokes (which may require work) return the engine to the initial condition with fresh steam. Cycling activity produces a net amount of useful work from hot steam.

In Truesdell’s device construction, one axiom is based on statements of Carnot: “Wherever a difference of temperature exists, there motive power can be produced.” “The motive power of heat is independent of the agents used to produce it; its value is determined solely by the temperatures of the bodies…” The First and Second Laws of thermodynamics are derived from these and other axioms.

A rather different mathematical device domain is occupied by electrical networks of resistances, capacitances and inductances. Primitive quantities include current and voltage; general axioms start with Kirchoff’s current and voltage laws. The domain expands to include transformers, transducers and transistors.

Similar methods are applied in § II.C.1 to construct a VE model for simple bursters.

Part II: Construction of a spinal assembly and associated Virtual Energy control devices that perform locomotion scripts.

A. Overview: Plan of construction

In four layers of progressive development, the project starts with a single force unit that models a twitching muscle fiber and grows into a spinal assembly augmented with terminal sticker devices, whose scripted locomotion movements along a wall are driven from a central command center. Operational structures resemble mathematical forms.

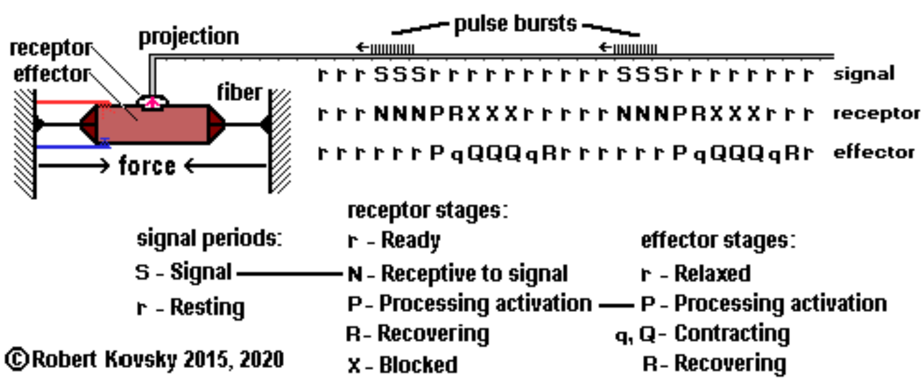
layers	stations	movements	measures
linear opposing forces	positions $\{k_i\}$. Balancing positions k_i – such a "k-index" is an integer in the set: [1, …, 15].	displacements. d(a,b) is a shift from position k_a to position k_b.	step measure. $m[d(a,b)] = \lvert k_b - k_a \rvert$. A measure of 1 step covers 1/14 of the range of motion.
angular joints controlled by opposing forces	bends $\{b_i\}$. Joints held at fixed angles, denoted b_i – a "b-index" is in: [–7, …, 0, …, +7].	flexions. δ(f,g) is a rotation from bend b_f to bend b_g. $b_m = \delta(0,m)$.	arc measure. $\theta[\delta(f,g)] = \lvert b_g - b_f \rvert$. A θ measure of 1 equals an arc measure of 6.4°.
spinal assemblies of angular joints	configurations. vectors represent configurations, e.g., $\underline{p} = (b_1, b_2, \ldots, b_8)$. Each joint in a spinal assembly has a bend denoted by a b_i in the vector.	deflections. $\underline{d}(\underline{p},\underline{q})$ moves from configuration $\underline{p}$ to configuration $\underline{q}$, with independent flexions of joints.	bending measure of a configuration **p**: $B = \Sigma b_i$ mismatch measure w of deflection $\underline{d}(\underline{p},\underline{q})$: $w[\underline{d}(\underline{p},\underline{q})] = \Sigma\lvert q_i - p_i\rvert$ with b-indices p_i, q_i
scripted movements of spinal assemblies	scripts. a succession of configurations; resembles a matrix in linear algebra, e.g.,{V, W, X, Y, Z}	variations. D(V, X) tracks changes from script V to script X	diff measure. $M[D(V, X)] = \Sigma D_{ij}$ $D_{ij} = \lvert X_{ij} - V_{ij}\rvert$

B. An initial repertoire of balancing positions and shifting movements (displacements) is produced by opposing twitches in a linear design.

1. Elemental twitches, force fiber device, pulse bursts, duet.

The ***force fiber device*** aims to model a muscle fiber. As shown in Fig. 5, a force fiber device has two chief parts: (i) a signal ***receptor*** that receives pulse burst signals; and (ii) an ***effector*** that produces forceful twitches and can thus perform mechanical work, e.g., lifting a weight. Initially, the force fiber device is fully extended to its maximum length and its ends are rigidly affixed to supports. A contractile force pulls inward but there is no movement.

Fig. 5. Twitching of force fiber device driven by pulse bursts



As shown in the figure, ***pulse bursts*** travel from right to left on a ***signal line*** or ***projection***. Projections resemble electrical wires and nerve fibers. A pulse is a fixed and instantaneous transfer of Virtual Energy; it resembles an action potential seen in nerves but is as fast as an electrical signal. Each burst consists of a series of pulses; and a fixed short time period intervenes between successive pulses. The number of pulses in a burst — or ***pulse number n*** — is an integer between 1 and 15. The pulse number specifies the strength of the ensuing twitch.

Operations of force fiber devices are organized by a unit of time called a ***tick***. A tick holds five pulses and five intervening periods. In Fig. 5, marks under the projection denote ticks. To start, a ***master clock*** controls ticking. Each pulse burst on the projection occurs during ticks denoted by `SSS` in code for the signal shown in the figure. Arrival of a pulse burst at the force fiber starts the receptor, which receives pulses for a period of three ticks, coded by `NNN`. Then, in a tick coded by P, joint ***processing*** in receptor and effector sets the strength of the pending twitch.

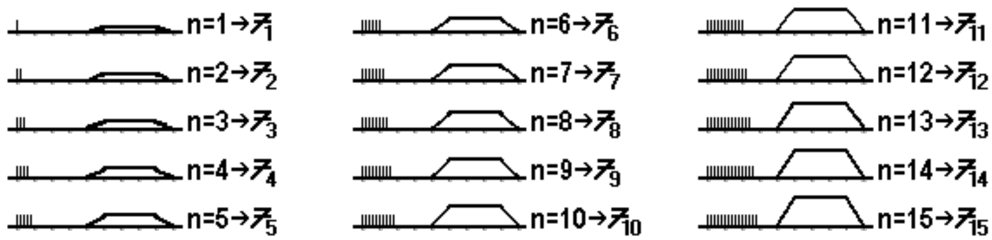
Processing is followed by a ***forceful contraction*** or ***twitching*** of the effector, coded by q and Q. The force strength of a twitch starts with minimal tautness and ramps up to the specified level in one tick, as coded by q. After a steady force for three ticks, coded by `QQQ`, the strength ramps down in one tick, again coded by q. There is a minimum of 8 ticks between first pulses of successive pulse bursts.

The NNNP code bloc in the receptor time line identifies a fundamental unit of time, a ***beat*** that consists of four ticks. Each cycle of operations of the force fiber device has two beats, a reception beat followed by a force beat. Dit-dah. Dit-dah. This cycle of operations is an example of a ***schema*** (pl. schemata), defined as a structure of actions adaptable to larger constructions. (See Piaget, 34 – 39).

Twitches are independent of each other; the weakest twitch can be followed by the strongest.

For a fully extended force fiber device, a burst of n pulses produces a twitch with a strength specified by the relation $\mathcal{F}_n = n \times \mathcal{F}_1$, where $\mathcal{F}_1$ is the strength of a twitch produced by a burst with 1 pulse. The full repertoire is shown in Fig 6:

Fig. 6. Repertoire of pulse-burst signals and forces of a twitching force fiber device



The relation between the pulse number and the force strength of a twitch is a ***linear relation***. Linear relations are used throughout the project with an expectation that non-linear variations may be investigated later.

Next: the design is developed to include variable lengths: if one end of the force fiber device is released from its support and allowed to shorten slowly, the force strength of the twitches decreases while n remains constant.

A revised force relation is introduced: $\mathcal{F}_n = (n \times \mathcal{F}_1) - (j \times \Delta L)$ — where ΔL denotes the shortening of the device and j is the ***dissipation factor***.

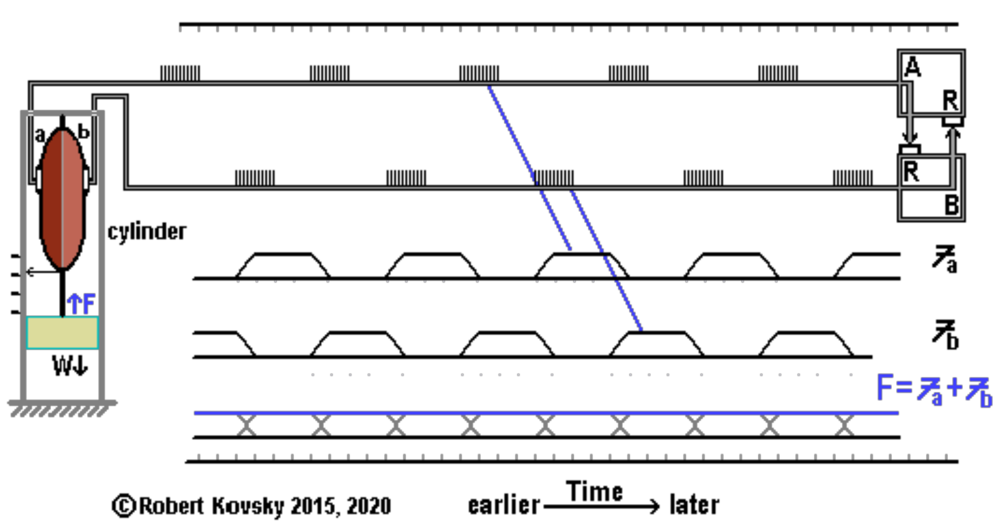
In part, the revised force relation resembles Hooke's law ($F = -k \times \Delta x$) that defines elastic materials and springs. In my experience, it is sometimes helpful to imagine springs or elastic bands operating in place of VE force devices. But j differs from k, the "stiffness" or "spring constant" used in Hooke's Law. Springy elastic materials store and release "conserved energy" that is based on k; but such energy is not stored in VE devices, where VE is lost through dissipation proportional to j and turned into heat, carried away by conduction through water. (Some VE designs also incorporate elastic materials; here, dissipative devices suffice.)

Other differences include a variable j in VE force devices, where needed, in contrast to the fixed k of Hooke's Law. A VE force device has a reference position at full extension and undiminished force; multiple values of n result in multiple positions at which $\mathcal{F}_n = 0$. In contrast, Hooke's Law has a reference position of $\Delta x = 0$ at which $F = 0$. (See Latash at 28-31, 126-130.)

The duet. In Fig. 7, showing a duet, the cylinder on the left contains a weight W and two force fiber devices, a and b. The force devices share physical connections and produce alternating twitches that combine to maintain the weight at a steady height. If a researcher slightly lifts or pulls down the weight, the system will relax into the former position when the external force is removed.

The duet has two ***reciprocating repeating bursting devices*** ("bursters"), A and B, shown on the right side of Fig. 7. When a burster discharges, it produces twin bursts of pulses: one burst travels on a projection to a force fiber device and the other burst travels on another projection to the other burster, which later discharges a burst. The size of an output burst of a repeating burster is the same as that of the input burst, indicated by an R in a burster. A researcher can change the size of bursts. Ticks are shown on lines at the top and bottom of the figure.

Fig. 7. Steady force produced by a duet:
two joined force fiber devices driven by two reciprocating bursting devices

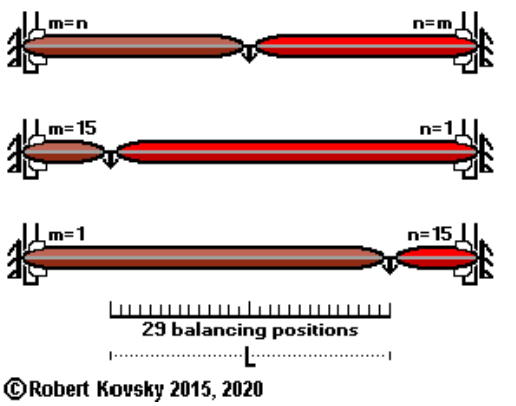


In other words, the duet produces a steady but variable force **F**, the strength of which is equal to $\mathcal{F}$, the central twitch strength in the ramp form. A steady **F** is patched together from alternating twitches; a successor twitch ramps up just as its predecessor twitch is ramping down. In Fig. 7, a blue line denotes the steady force: $F = \mathcal{F}_a + \mathcal{F}_b$. Ramping parts of twitches are shown in gray below the steady blue line. In sum: when W is steady, bursts with n pulses are being delivered on an alternating schedule to the two force fiber devices, producing a steady force F_n.

2. Variable drive signals sent to two duets operating in linear opposition produce a spectrum of balancing positions.

Fig. 8 shows two duets, each affixed to a rigid support at one end and connected to a shared mobile ***indicator arrow*** at the other end. Forces produced by the duets are in opposition; one duet pulls the indicator arrow to the right and the other duet pulls it to the left. When forces are in balance, the indicator arrow is stationary. Outside the figure, the researcher controls the pulse numbers and sends bursts with m pulses to the left duet and bursts with n pulses to the right duet.

Fig. 8. Two equal and opposing duets produce a spectrum of balancing positions



In the top image, equal pulse bursts arrive at both duets: m = n or n = m. The indicator arrow is centered at a position called ***midline***. Equal forces and an indicator arrow at midline are produced by equal pulse bursts of every size, from 1 to 15.

An end-of-range position occurs when one duet is driven by bursts with pulse number 1 and the other duet is driven by bursts with pulse number 15, as shown in the bottom two images of the figure.

Duets in linear opposition can hold the indicator arrow at 29 equally spaced ***stationary balancing positions*** that are defined by $x = (n–m) \times L/28$, where x denotes the distance from midline measured to the right; (n-m) is both the difference in pulse numbers and also the number of steps from midline to the right; L is the size of the range of motion; and L/28 is the size of one step.

When n>m, x is a positive number and balancing positions are to the right of midline. When m>n, x is a negative number and balancing positions are to the left of midline. Except at endpoints, multiple pairs of (m,n) hold the balance at each position. A pair of (m,n) pulse burst signals is called a ***drive signal***. For example, the balance is held at 6 steps to the right of midline by the following drive signals:

(9, 15), (8, 14), (7, 13), (6, 12), (5, 11), (4, 10), (3, 9), (2, 8) and (1, 7).

3. Restrictions on balancing positions and drive signals simplify the construction and result in a variety of activations.

Beneficial restrictions are imposed on allowable positions and signals in the opposing duet design. The range of motion is restricted to the 15 positions centered around midline. Each position is produced by exactly one pair of drive signals. The restrictions organize various sets of drive signals, called activations.

The indicator arrow is at the left in the first position of all the sets below. In Group 1, smaller signals are at midline and larger signals cause movements away from midline. Labels of activations – rigid, versatile, delicate – refer to responsiveness to external forces. The midline drive signal – 8, 5, 1 in the examples – specifies the level of activation.

In Group 2, the largest signals and strongest forces are at midline. Movements away from midline require relaxation of the duet on the side opposite to the movement. A movement from midline to the left requires diminution of drive signals in right bursters while left bursters maintain steady midline drive signals.

Group 1:

most rigid:	(15, 8), (14, 8), (13, 8), (12, 8), (11, 8), (10, 8), (9, 8) (8, 8) (midline) (8, 9), (8, 10), (8, 11), (8, 12), (8, 13), (8, 14), (8, 15)
versatile:	(12, 5), (11, 5), (10, 5), (9, 5), (8, 5), (7, 5), (6, 5) (5, 5) (midline) (5, 6), (5, 7), (5, 8), (5, 9), (5, 10), (5, 11), (5, 12)
most delicate:	(8, 1), (7, 1), (6, 1), (5, 1), (4, 1), (3, 1), (2, 1) (1, 1) (midline) (1, 2), (1, 3), (1, 4), (1, 5), (1, 6), (1, 7), (1, 8)

Group 2:

most rigid:	(15, 8), (15, 9), (15, 10), (15, 11), (15, 12), (15, 13), (15, 14) (15, 15) (midline) (14, 15), (13, 15), (12, 15), (11, 15), (10, 15), (9, 15), (8, 15)
versatile:	(12, 5), (12, 6), (12, 7), (12, 8), (12, 9), (12, 10), (12, 11) (12, 12) (midline) (11, 12), (10, 12), (9, 12), (8, 12), (7, 12), (6, 12), (5, 12)
most delicate:	(8, 1), (8, 2), (8, 3), (8, 4), (8, 5), (8, 6), (8, 7) (8, 8) (midline) (7, 8), (6, 8), (5, 8), (4, 8), (3, 8), (2, 8), (1, 8)

As discussed in the next section, this project investigates certain slow controlled movements. The highest level of force or most rigid Group 2 activation is used for investigations into such movements. There are several reasons for this choice.

(1) The most rigid Group 2 activation appears to be least subject to perturbations and best able to hold a position. (2) The range of forces between midline and end-of-range positions is least in the most rigid Group 2 set, namely, 15/8 to 15/15 or about 2:1. The corresponding range of forces in the most delicate Group 2 set is 8:1. The lower ratio is easier to realize and closer to that produced by animal muscle. (3) Better control appears to be provided by Group 2 activations where movements away from midline depend on relaxation rather than a pulling force.

Let index k_i or k specify the position of the indicator arrow from left to right. Thus k or $k_i \in \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15\}$. When k = 1, the indicator arrow is at the left edge of the restricted range of motion; when k = 15, it is at the right edge. Midline is indexed by k = 8.

The following table shows the relationship between positions of the indicator arrow **k** and drive signals **s** in the most rigid Group 2 set.

k	1	2	3	4	5	6	7	8
s	15,8	15,9	15,10	15,11	15,12	15,13	15,14	15,15
k	8	9	10	11	12	13	14	15
s	15,15	14,15	13,15	12,15	11,15	10,15	9,15	8,15

When operations are thus restricted to a single activation and to a single specified set of drive signals, the position of the indicator arrow can be represented by a single burst with k pulses – rather than by a pair of bursts in a drive signal.

4. A device displacement is a detached overdamped shifting movement between two balancing positions.

Next come movements of the linear opposing-duet system. In a "shifting movement," the indicator arrow starts at one stationary position, then pulse numbers change, then there is a smooth movement, and the indicator arrow ends up at another stationary position. In comparison, movements that start with a jerk are called "saccades" or "saccadic." Movements of eyes of human beings follow the saccadic form, as do jerky movements of birds on the ground. Shifting movements and saccadic movements are similar but shifting movements are slower.

Suppose that the linear opposing-duet system starts with signals (12, 15), k = 11; then signals are changed to (15, 9) and the indicator arrow moves to k=2; then signals are changed to (15, 10) — another movement occurs and the indicator arrow ends up at k = 3.

We are not concerned here with how much time a movement requires. Saccadic movements can be extremely forceful, e.g., a kick or punch, but here we are investigating slower shifting movements. In both cases, a sudden force difference caused by the change in signals starts the movement. Here, force devices and surrounding water have ***material properties*** that slow movement and return devices to a stationary condition — dissipative properties sometimes called "damping" or "viscosity."

Dissipations are presumed to be sufficient so that at the end of every movement, even a forceful movement caused by a signal change from (8, 15) to (15, 9), the indicator arrow ***relaxes into*** and stops at its final position. In a Hooke's Law or elastic system similar to this system, such a condition is said to be "overdamped." With so much dissipation, the indicator arrow does not stretch beyond the final position and then pull back. In contrast, an "underdamped" Hooke's Law system will stretch past the final position, pause and then pull back.

A period of rest intervenes between any two movements; and a rest period can be prolonged without changing results of subsequent movements. Movements are thus ***detached*** from one another. In thermodynamics constructions discussed above in I.C.5, similar movements and changes are called "quasi-static." Such detached, quasi-static, overdamped movements provide a convenient, rational starting place for investigations into all classes of movements.

Assimilating the construction to standard mathematical paradigms, a detached shifting movement of the linear opposing-duet design is called a ***device displacement***.

5. Device displacements are organized by an operational structure that resembles the mathematical displacement group.

The set of displacements in the opposing-duet design resembles a mathematical group. This group is simple; it is developed into more complex forms below — into configurations of an 8-joint angular assembly and then into scripts that contain a succession of configurations and that are processed by quadnets with m × n blocs of devices in arrays that resemble matrices of linear algebra.

A displacement begins at a starting position and ends at a final position. Denote a displacement as d(a,b) where "a" is the k-index of the starting position and "b" is the k-index of the final position. For example, a displacement that starts at the position with k = 10 and that ends at the position with k = 4 is denoted as d(10,4).

If a second displacement follows a first displacement, they are ***composed***: $d(a,b) \oplus d(b,c) = d(a,c)$ where $\oplus$ denotes composition. Disregarding quasi-static details, "the same" shift is produced by (1) two displacements that share an intermediary position and by (2) a single displacement whose change in indices is "composed" of the terminal indices of the two displacements.

Define ***null movements*** d(z,z) for all positions z. A null movement starts and ends at the same position. It is actually no movement at all. Denote any null movement by d_0. Then, $d(a,b) \oplus d_0 = d(a,b) \oplus d(b,b) = d(a,b)$ using the composition rule. (In mathematical groups, it should be noted, the null or identity element is unique.)

Also: $d(f,g) \oplus d(g,f) = d(f,f) = d_0$. A movement from position f to position g followed by a movement from position g to position f can be said to be the same as no movement at all, as if never leaving position f. Adapting mathematical terms, d(f,g) and d(g,f) are ***inverses*** of each other and displacements are ***reversible***.

Further: $[d(w,x) \oplus d(x,y)] \oplus d(y,z) = d(w,y) \oplus d(y,z) = d(w,z) = d(w,x) \oplus d(x,z)$
$= d(w,x) \oplus [d(x,y) \oplus d(y,z)]$

In words: displacements inside a pair of brackets are composed first and changing the order of composition does not change the result.

The restricted linear opposing-duet design has 15 possible starting positions and 15 possible ending positions; or 225 possible displacements, including 15 null movements. Every displacement in the restricted set is distinct from every other displacement.

The foregoing set of displacements resembles the mathematical ***group of displacements***. As an operational structure, the device set is closed under the composition operation: a composition of two displacements in the set is also a displacement in the set. For every displacement in the set, there is an "inverse displacement" that returns to the prior position. A displacement followed by its inverse displacement is a "null displacement." Composition of a displacement with a null displacement is the same as the original displacement. The order of composition of displacements does not change the final resulting displacement.

Mathematics also suggests a way to ***measure the size*** of a displacement. Thus, define "$m(k_1, k_2)$" or "the distance measure from position k_1 to position k_2" as $m(k_1, k_2) = | k_2 - k_1 |$ where k_1 and k_2 denote k-indices and $| x |$ denotes the absolute value of x.

For example, a displacement from $k_1 = 10$ to $k_2 = 4$ travels a distance of 6 steps. Thus $m(10, 4) = 6$. The same distance is traveled during a displacement from $k_1 = 4$ to $k_2 = 10$.

That is: $m(k_1, k_2) = | k_2 - k_1 | = | k_1 - k_2 | = m(k_2, k_1)$.

Also $m(k_x, k_x) = 0$ for all k_x.

The distance measure is applied to the composition of two displacements. Given $d(k_1, k_3) = d(k_1, k_2) \oplus d(k_2, k_3)$, the rule for composition of the measure is $m(k_1, k_3) \leq m(k_1, k_2) + m(k_2, k_3)$ or $| k_3 - k_1 | \leq | k_2 - k_1 | + | k_3 - k_2 |$. If the displacements are in the same direction, the composed distance is equal to the sum of the separate distances. If the displacements are in opposite directions, the composed distance is equal to the difference between the separate distances.

The distance measure applies in a uniform way at every position in the range of motion and for every distance between positions. The uniformity of the distance measure depends on underlying linear structures that are preserved in later stages of the construction.

C. Burster modules drive displacements in the opposing-duet design.

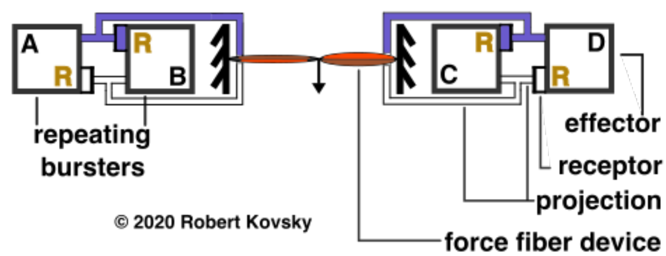
Opposing duets are controlled by ***burster modules***, shown in a series of designs. At the start of the series, the master clock, like an orchestra conductor, controls all timings of devices; but this requirement will be overcome to some extent at the end. Designs acquire additional symbols that participate in math-like constructions.

1. Holding module made of repeating bursters; operational codes; VE schema for the repeating burster.

Opposing force fiber duets are shown below, along with the Virtual Energy devices that drive them, namely, four ***repeating bursters*** (**A**, **B**, **C**, **D**) in two reciprocating arrangements. The two force fiber duets and four bursters make up a ***module*** that performs the function of holding the indicator arrow at a set of stationary positions.

In Fig. 9, violet projections carry pulse bursts from burster A to the upper left force fiber and to burster B; and similar bursts travel from burster D to burster C and to the upper right force fiber. At the moment shown, both lower force fibers are forcefully contracting and maintaining the tense balance.

Fig. 9. Two pairs of reciprocating bursters driving linear opposing duets



The brown "R" at the receptor of each device indicates that they are repeating bursters. First, burster A sends m pulses to burster B (and to a force fiber); then burster B sends m pulses to burster A (and to a force fiber); and then the cycle repeats. Burster parts are labeled in the figure; these parts resemble those of a force fiber device. Pulses travel the same on projections regardless of devices that send or receive them. Both kinds of receptor (in the force fiber device and the burster) receive n pulses and use n to set a value for effector action. A force fiber effector produces a twitch while a burster effector produces a burst of pulses. Both effectors contain a Virtual Energy Store (VES) that receives, stores and converts the VE needed for force production or pulse production.

Operations of bursters are described by ***charts*** and ***codes*** that resemble musical scores and notes. Elements of movement introduced above in § B.1 are coded in charts – ***schemata*** – and are then developed into extended movements or sequences that resemble musical melodies. Charts are organized by temporal units that resemble musical time signatures (march, waltz, 4/4). In the first designs, four ticks make up a beat and two beats make up a schema. "Two beats to a schema" imposes a tight but clear constraint. In quadnet operations in the scriptorium discussed below, more flexible schemata are also used.

Code symbols were introduced above for the force fiber device. In place of a contractile force denoted by qQQQq, a burster discharge of a pulse burst is denoted by OOO. The following chart shows essential code for the 8 device parts in the holding module shown above. The order of lines in the chart can be re-arranged without changing anything.

```
A-eff         OOOR   POOOR   POOOR   POOOR   POOOR   PO
B-rec         NNNP    NNNP    NNNP    NNNP    NNNP    N
B-eff            POOOR   POOOR   POOOR   POOOR   POOOR
A-rec             NNNP    NNNP    NNNP    NNNP    NNNP
left/up rec   NNNP    NNNP    NNNP    NNNP    NNNP    N
left/up eff      PqQQQq  PqQQQq  PqQQQq  PqQQQq  PqQQQq
left/down rec     NNNP    NNNP    NNNP    NNNP    NNNP
left/down eff        PqQQQq  PqQQQq  PqQQQq  PqQQQq  Pq

C-eff         OOOR   POOOR   POOOR   POOOR   POOOR   PO
D-rec         NNNP    NNNP    NNNP    NNNP    NNNP    N
D-eff            POOOR   POOOR   POOOR   POOOR   POOOR
C-rec             NNNP    NNNP    NNNP    NNNP    NNNP
right/up rec  NNNP    NNNP    NNNP    NNNP    NNNP    N
right/up eff     PqQQQq  PqQQQq  PqQQQq  PqQQQq  PqQQQq
right/down rec    NNNP    NNNP    NNNP    NNNP    NNNP
right/down eff       PqQQQq  PqQQQq  PqQQQq  PqQQQq  Pq
```

In the following extract, pulse burst 552 specifies position 12, with 5 pulses in the first tick, 5 pulses in the second tick and 2 pulse in the third tick. During the first beat, a pulse burst is discharged from A-eff (552) and received by B-rec (552), a single event shared by both bursters. Next, B's receptor and effector both process the burst during the P tick, ending the first beat. In the second beat, B's effector discharges the pulse burst (552), as noticed by A's receptor (552). During the P tick of the second beat, A processes the burst (P connects the fourth and first lines). Next, during the third beat, A discharges a pulse burst, repeating the schema.

```
A-eff  552    P552    P552    P552    P552
B-rec  552P    552P    552P    552P    552P
B-eff     P552    P552    P552    P552    P552
A-rec      552P    552P    552P    552P    552P
```

```
A-eff  X X X X X
B-rec  X X X X X
B-eff   X X X X X
A-rec   X X X X X
```

In ***condensed code***, a symbol stands for one beat or four ticks. The adjacent condensed code extract represents the same activity as the version above. X = burst 552.

The Virtual Energy model for bursters resembles a Conserved Energy model.

As discussed in § I.C.5, the concept of Virtual Energy (VE) is adapted to diverse applications. Applications in this project combine aspects of Internal Energy, the Carnot heat engine and electrical networks.

General principles.

1. ***Virtual Energy*** (VE) is an invented concept that resembles energy concepts of science but including ambiguities and allowing for further *ad hoc* inventions. VE appears in ***VE devices*** in multiple forms. VE devices are defined in terms of ***device operations*** that involve ***VE conversions*** from one form to another form.

2. One form of VE is ***pulses***. Pulses are uniform and each pulse carries one unit of VE denoted as ! and called a "bang." Pulses travel on ***projections***, which are uniform devices that carry pulses from a producing device to a receiving device.

3. Each device contains a ***Virtual Energy Store*** (VES). A VES can hold a variable quantity of VE up to a maximum ***capacity***. Definitions of device operations include specifying the momentary quantity of VE in the VES at the start and end of each operation. This quantity is denoted by ***V(t)***. [In this project VE is quantifiable at all moments. I presume that some "phase change" operations in quadnet devices include critical moments when VE is not quantifiable.]

4. All conversions involve VE losses or ***dissipation***. Lost VE is presumed to vanish into the environment. No new VE appears in any conversion. For purposes of simplicity, loss is reduced to zero in certain ***idealized*** operations. "Realistic" losses can be added to idealized operations without changes in function by means of, e.g., a larger VES, larger VE flows, auxiliary VES, faster operations, delays.

Application. The ***repeating burster*** operates according to a schema of 8 ticks that has periods of signal reception, preparation, pulse production and restoration. Schemata can follow one another, either immediately or occasionally, but cannot overlap in time. The device waits in readiness while there is no signal. It's function is specified by the formula "k pulses input, k pulses output."

a. The VES in the repeating burster device has a capacity of $V_1 – V_0 = 15!$. At all moments, $V(t) \geq 0$ traces the quantity of VE in the VES. At the start and end of a schema, $V(t) = V_1$.

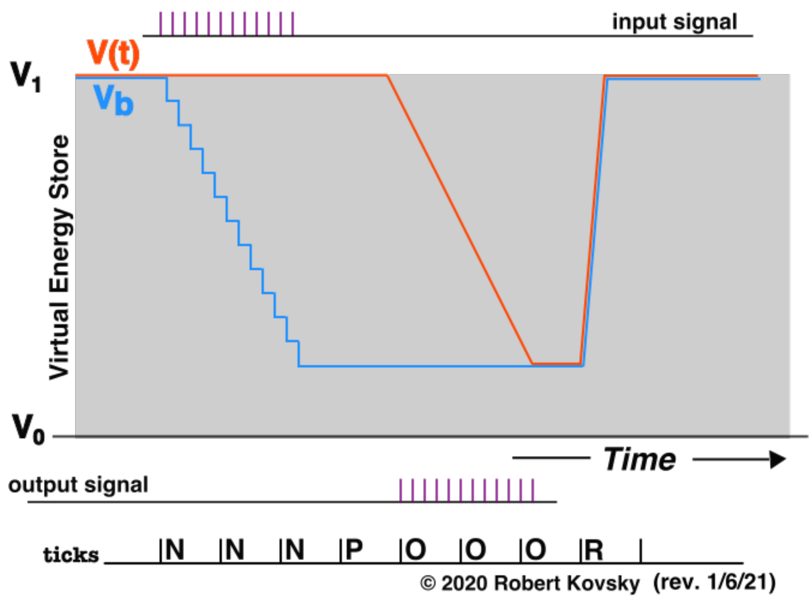
b. The source of VE for pulse production is provided by a ***VE inflow stream*** which puts VE into the VES during a restoration operation at the rate R > 16!/tick.

c. A device part, ***an output projection***, extends from the device to an input receptor of another device and carries pulse bursts. A burst of k pulses carries k! of VE, discharged from the VES during a production operation.

d.	A part of the device, an ***input*** or ***burst receptor***, receives a pulse burst that arrives during a reception operation through a projection from another burster.

e.	A ***device setting***, $\boldsymbol{V_b}$, is used to specify the number of pulses involved in a particular cycle of operations. At the beginning and end of a schema, $V_b = V_1$.

Fig. 10. VES operations of a repeating burster (k pulses input, k pulses output)



f.	Fig. 10 shows operations of the repeating burster.

(1)	In an idealized restoration operation, during the recovery tick **R** at the end of the schema, VE in the inflow stream is converted into VE stored in the VES, until V(t) reaches the maximum capacity V_1. V_b tracks along with V(t).

(2)	In a lossy operation, during reception ticks **N** in the schema, each incoming pulse shifts V_b down one ! in the VES. Unused VE in the pulse is dissipated. The number of steps down equals the number of pulses in the input burst. In Fig. 10, there are 12 pulses and 12 steps down; the final $(V_1 – V_b)$ = 12!.

(3)	In an idealized pulse production operation, during **P** and **O** ticks in the schema, V(t) is driven down from the maximum amount V_1 to the level set by V_b at a rate of 5!/tick. The number of pulses in the output burst equals $(V_1 – V_b)$/!.

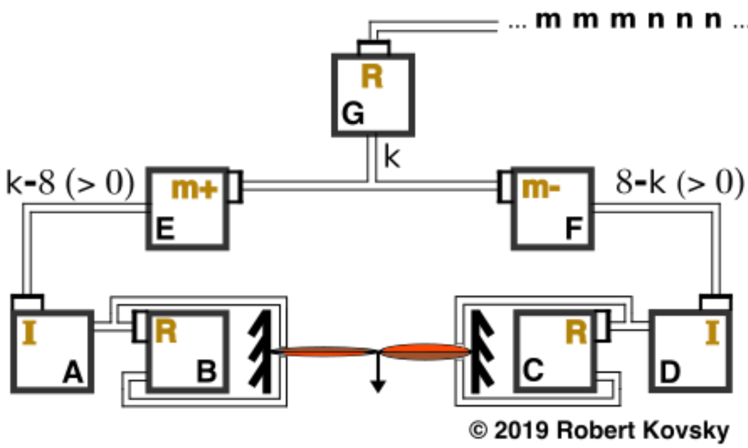
When V(t) is driven down, the amount of VE in the VES is lowered and excess VE is converted into pulse discharges. V_b is a variable device setting that specifies the point at which discharge stops. V(t) resembles the temperature in a steam engine. Suppose that, in a steam engine, the initial temperature of the steam is 500° C. If the temperature is driven down from 500° to 400°, a certain amount of work is produced. If the temperature is driven down from 500° to 300°, more work is produced. V_b is like the lower temperature in a steam engine process.

2. Module for streaming input; VE schemata for added bursters.

The next version produces movements of the indicator arrow. The module shown in Fig. 11 processes a ***stream*** of pulse bursts. Pulse bursts arrive every 8 ticks. Former bursters **A** and **D** are changed and new bursters **E**, **F** and **G** are added.

As before, devices operate according to cycles and beats that are set by a master clock. Every cycle, a burst arrives at burster **G,** specifying the k index and position of the indicator arrow in an upcoming cycle. To accommodate the detached shifting form of movement, the bursts in the stream maintain a particular pulse number for a lengthy period of time. Changes are isolated and occasional. The pulse number is repeated with m pulses while the system stays at rest and then the pulse number is changed to n, which is again repeated until after the indicator has finished moving. Note the absence of reciprocating projections from burster **B** to burster **A** and from burster **C** to burster **D**. Here, "holding" of the indicator arrow is maintained by a streaming input signal of constant value rather than by reciprocating bursters.

Fig. 11. Streams of pulse bursts driving linear opposing duets



Operations in bursters **G**, **B** and **C** follow the repeating burster schema ("k pulses in" produces "k pulse out"), as denoted by the brown "**R**"; but operations in bursters **A**, **D**, **E** (**m+**) and **F** (**m-)** have different schemata.

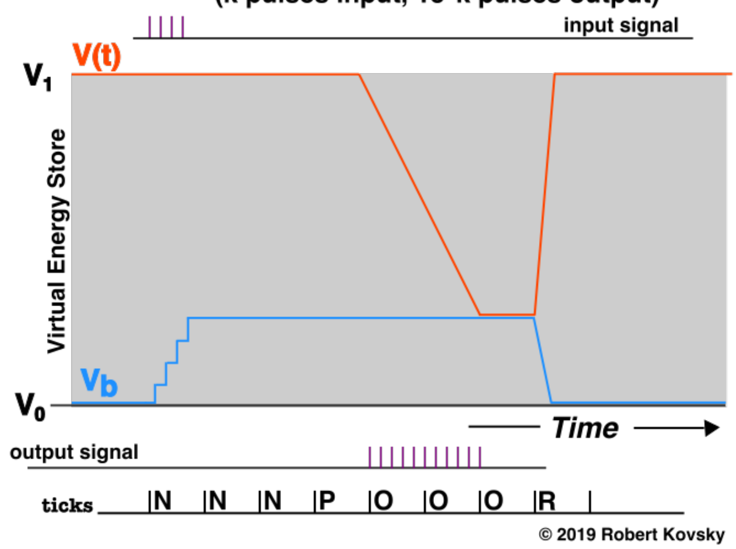
The **I** in bursters **A** and **D** denotes an ***inverting operation***: k pulses in produces output of (15 – k) pulses. The **m+** and **m-** bursters have the function of relating a k-index to midline; k pulses in produces, at most, one output of k–8 or 8–k pulses.

In a stream, bursts with m pulses arrive at **G**; bursts with m pulses are then discharged from **G** onto **E** and **F**. Processing operations in **E** disregard the first 8 pulses in an arriving burst and output k–8 pulses, if k > 8; if k ≤ 8, there is no output from **E**. E.g., if k=12 the output from **E** is 4 pulses. Operations of **E**, denoted by m+, are called ***right-of-midline*** because output pulses count steps right of midline; e.g., k=12 specifies the position four steps to the right of midline.

In the schema of an inverting burster shown in Fig. 12, the pulse production process that occurs during OOO ticks is the same as that in the repeating burster and the number of output pulses is again $(V_1 - V_b)/!$. Differences revolve around V_b; V_b starts at V_0, at the lowest energy level of the VES. $V_1 - V_0 = 15!$

When the designated position of the indicator arrow is to the left of midline, k < 8 and no pulses arrive at **A** to change V_b from $V_b = V_0$: device **A** produces 15 pulses output. When movement is to the right, k > 8, pulses arrive at the **I** receptor of **A**, V_b is raised step by step and the output pulse number of **A** is reduced from 15 by the number of arriving pulses (varying from 1 to 7). In the example in the figure below, input is 4 pulses and output is 11 pulses.

Fig. 12. VES operations of an inverting burster
(k pulses input, 15-k pulses output)



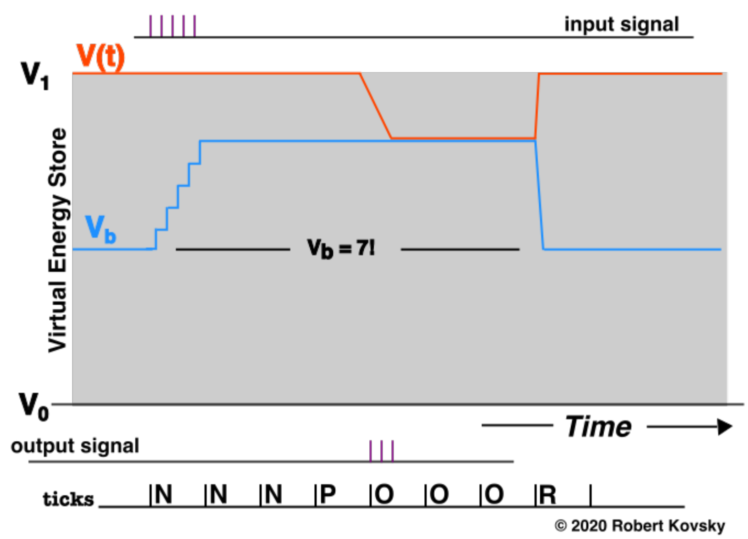
In Fig. 12, the incoming bursts has pulse number 12, so k–8 = 4 pulses arrive at the receptor of **A**; V_b is raised; and **A** produces a burst with 11 pulses. Drive signals (11, 15) thus produce the position with k-index 12, as desired. (See § B.3.)

In sum, pulses that count steps to the right are sent to the left inverter burster where they reduce the strength of left forces.

Similarly, operations in **F**, the ***left-of-midline*** or **m-** burster, produce output pulses during OOO ticks with a pulse number that is equal to 8–k, when k is the input pulse number. As with prior bursters, the number is $n = (V_1 - V_b)/!$. Similar to the inverter, the output pulse number is reduced by one for each input pulse. If k equals or exceeds 8, $V_b = V_1$ and there is no output.

Suppose that a burst with 5 pulses arrives at the m- burster. Operations are shown in Fig. 13. V_b in the burster is initially set at 7!, producing 8 pulses if there is no input. V_b is raised by 1! for each arriving pulse.

Fig. 13. VES operations of left-of-midline (m-) burster (k pulses input, 8-k pulses output)



In the example, 5 arriving pulses indicate k-index 5 and the output of **F** is a burst with 8–k=3 pulses, which arrive at **D.** The output pulse number from **D** is reduced from 15 to 12. Drive signals are now (15, 12), relaxing the right mover 3 steps and allowing the left mover to pull the indicator arrow 3 steps to the left from position 8 to position 5, in accord with the original arriving burst.

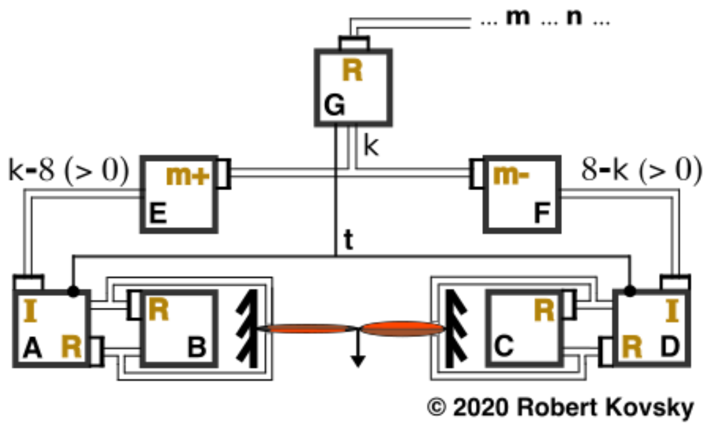
In sum, operations in **E** and **F** control distances from midline and reflect the fact that a movement away from midline to one side requires relaxation of the mover on the other side, opposite to the movement. If k=8, there are no reduction pulses on either side and the midline position of (15, 15) is produced.

3. Two mode module for occasional changes.

Features in the two preceding designs are combined: the new module has two distinct modes of operation. In holding operations, reciprocating bursters maintain the stationary position specified by the most recently arrived burst. A new burst resets the position; and the new position is held until the next new burst. Arriving bursts are "occasional," with enough intervening time for movement to cease.

In Fig. 14, **A** and **D** have a default holding mode and an occasional substitution mode. In holding mode, operations of **A** and **D** are the same as in the holding module; reciprocating projections carry pulse bursts to R receptors. In substitution mode, operations of **A** and **D** are based on inverter operations, as in the streaming module above; and pulses are received through **I**. During substitution mode, R receptors of **A** and **D** are blocked and inoperative. When an occasional pulse burst arrives at **G**, **G** sends a ***switching pulse*** over the **t** line to **A** and **D**, causing them to switch modes for the next cycle; they then switch back for later cycles.

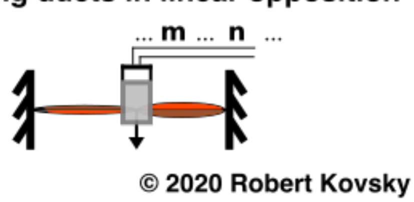
Fig. 14. Occasional pulse bursts switch bursters between modes



In another change in operations, the master clock is replaced by a ***modular clock***, which is independent of other modular clocks. A burst can arrive at **G** at any time, rather than having to be in synchrony with cycles and beats of **G**. **G** holds the arriving burst until it fits into the next available cycle set by the modular clock.

In the style of biological cells or electronics chips, the two-mode burster module is reduced to the small unit shown in Fig. 15 that is carried on the duets above the indicator arrow. Occasional bursts sent over the projection to the module move the indicator arrow from position to position.

Fig. 15. A burster module driving duets in linear opposition



Essential code for the schema of the two-mode module is set forth below, with the example of an occasional pulse burst with 11 pulses or 551 in three ticks. In additional device operations, **!** denotes a switching pulse on the **t** line, traveling from a timing device output on G over projections to input points on A and D. `XXX` denotes blocking of a receptor; `???` denotes signals that are superseded.

In the code below, the final tick of the `551` burst arrives at `G-rec` within a "window," an 8-tick time interval that can be variably defined. Here, the window stretches between the 7th ticks of two cycles of the modular clock. Using terms and symbols adapted from set theory, the 8-tick time interval is closed at the earlier terminus and open at the later terminus. Windows are "tiled" to fill the time line: whenever a burst arrives at **G**, the third N tick occurs in a window and the burst is processed at the next available opportunity.

After the arriving burst is processed by **G**, **F-rec** inputs burst `551` and **F-eff** outputs nothing (`000`); therefore, **D-eff** outputs the midline signal, 15 pulses or 555. **E-rec** inputs `551` and outputs `300`. Inverting burster **A-eff** outputs 12 pulses or `552`. As desired, (12, 15) is the drive signal for position 11 of the indicator arrow. (See the table at the end of § II.B.3.)

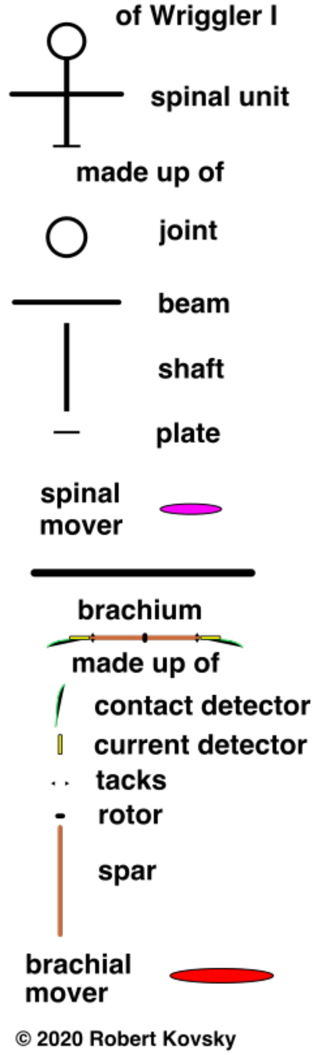
```
Schema for two-mode burster module

G-rec  |[--551-)_P
G-eff  |         P551
G-t-o  |         !
F-rec  |          551P
F-eff  |             P000
E-rec  |          551P
E-eff  |             P300
D-t-i  |         !
D-I    |              000P
D-R    | P    ???P    XXX     555P    555P
D-eff  | P???    P???    P555    P555
C-rec  |  ???P    ???P    555P    555P
C-eff  |    P???    P???    P555    P555
A-t-i  |         !
A-I    |              300P
A-R    | P    ???P    XXX     552P    552P
A-eff  | P???    P???    P552    P552
B-rec  |  ???P    ???P    552P    552P
B-eff  |    P???    P???    P552    P552
```

D. In an adaptation of the linear design, a rotating joint produces balancing positions with a spectrum of angles called bends.

1. Body parts of Wriggler I

Fig. 16 shows body parts of Wriggler I. Spinal parts are in the top section of the figure; brachial (limb) parts are in the bottom section. The remainder of this project focuses on spinal assemblies built from spinal units and spinal movers.

Fig, 16. Body parts of Wriggler I



The spinal unit is a rigid construction of parts: circular joint, beam, shaft and plate. The shaft is attached to the joint at one end and to the plate at the other end. The beam is attached at right angles to the shaft not far from its center.

In the spinal unit as a whole, the length of the beam is equal to twice the distance from the center of the joint circle to the beam; this feature defines geometrical squares in centered positions of a spinal assembly. Larger geometrical squares are defined by brachial spars in centered positions.

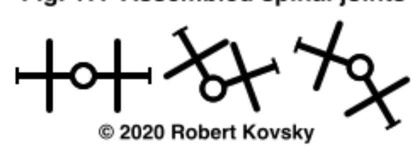
As one way to assemble spinal units, plates of two units are rigidly attached The two shafts must be exactly aligned for assembly. In anticipated developments, a couple of stress detectors operate between two assembled plates.

Two spinal units are also assembled by superimposing and combining their circular joints. Each joint rotates with respect to the other around the common center. Hubs of bicycle wheels that run on ball bearings are suggestive of designs for rotating joints.

Movers in spinal assemblies (and in brachial assemblies) operate the same as duets made of force fiber devices previously discussed but using different names and images.

In Fig. 17, spinal units have been assembled at the joint. Two units rotate about a common axis and have a range of positions with respect to each other.

Fig. 17. Assembled spinal joints



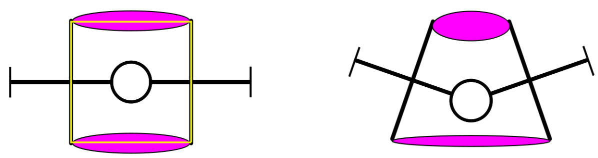
2. Rotational adaptations of the linear design: spinal segments, angular balancing positions in a spectrum, bends

[Addendum 4/30/22. A later spinal segment design in the 2021 *Metamorphosis* project at p. 29 overcomes problems discussed in this section. "The new hub joint produces bends from drive signals that duplicate those in the prior design."]

The linear opposing-duets design is adapted to produce angular positions of rotating joints. As in the linear design, a set of drive signals produces a set of stationary balancing positions, but now with variable angles or ***bends***.

The ***spinal segment*** is an elemental construction. An enlarged image of a spinal segment is shown if Fig. 18 in two positions. Instead of duets in linear opposition, movers are in angular opposition. In the centered position on the left, the yellow square drawn in the movers and beams outlines a useful geometry.

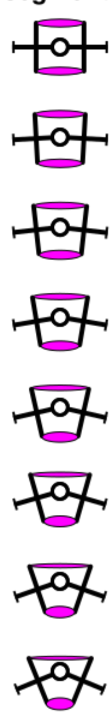
Fig. 18. Two movers in angular opposition



The spectrum of balancing positions for spinal segments is shown in Fig. 19. Drive signals produce equally-stepped angular bends that resemble prior displacements from midline. There is a complication in that torques must balance at the center of a joint and the shorter mover has a larger moment arm than the longer mover, resulting in a larger torque. To produce equality of steps, the dissipation factor j is varied according to the length of the mover.

Another adjustment is a shortfall (44.8°) from a geometrically ideal maximal joint angle of 45° — which results in a range of motion divided into seven equal angular steps of 6.4° each, a useful simplification.

Fig. 19. Spinal Segments of Wriggler I



spinal segments	drive signals	angles	bends
	15 15	0.0°	0
	14 15	6.4°	1
	13 15	12.8°	2
	12 15	19.2°	3
	11 15	25.6°	4
	10 15	32.0°	5
	9 15	38.4°	6
	8 15	44.8°	7

Shifting movements of linear opposing duets are easily adapted to the angular joint. Burster modules operate identically in the two applications; small reduced modules are located inside each angular joint, like the final design of the linear arrangement.

Similar to the stepped balancing positions $\{k_i\}$, the angular joint has a set of stepped bends $\{b_i\}$. In place of the k-index for balancing positions, bends in the angular joint are represented by a ***b-index*** where

$b_i \in \{-7, -6, -5, -4, -3, -2, -1, 0, +1, +2, +3, +4, +5, +6, +7\}$.

Bends on the two sides of the angular joint are symmetrical. Movements to one side are given a – sign and movements to other side are given a + sign. The integral number denoting a bend states the number of steps from the centered position.

An extreme bend with $b = -7$ is assigned the position $k = 1$; then $k = b + 8$; and this relation holds for the entire set. E.g., position $k=11$ is the same as $b=+3$.

Movements of angular joints are called ***flexions*** (similar to displacements). A flexion $\delta(f,g)$ is a rotation of the joint from bend b_f to bend b_g. Group features of displacements are carried over directly to flexions.

The measure of a flexion is called ***arc measure***. Each unit of arc measure = 6.4°. Arc measure is denoted by θ and the value is calculated:

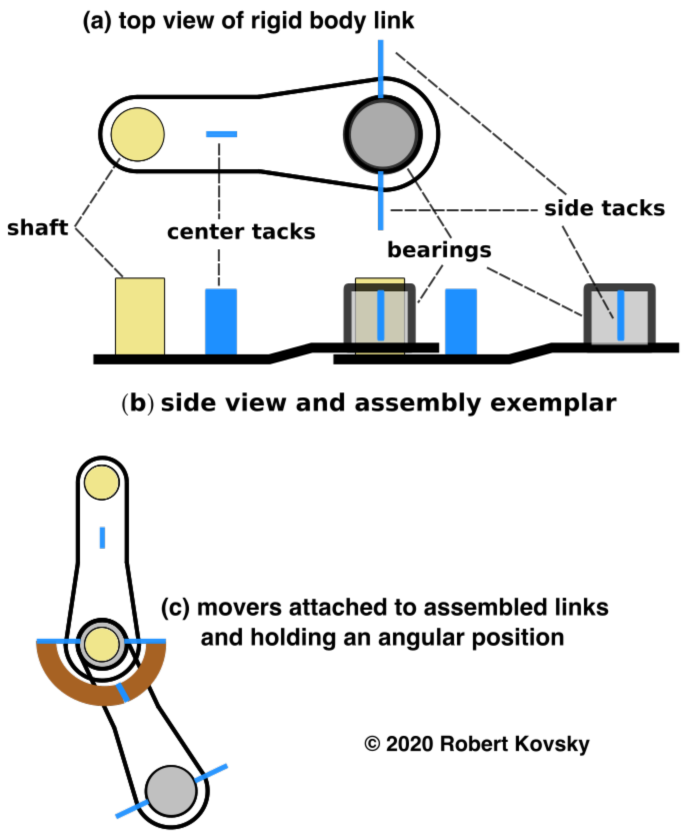
$\theta[\delta(f,g)] = |b_g - b_f|$.

For example, a flexion from bend +5 to bend –4 has 9 units of arc measure or 57.6°.

One shortcoming of the design is that positions are stable in the two dimensions of planar images but would be unstable in the third dimension that is perpendicular to the images. In other words, if a spinal segment were to be made of actual planar materials, the opposing pair of movers would, unless constrained, pull the shafts and beams out of the plane of the page. The parts would bend and rub against each other, making movement impossible or very difficult.

The three-dimensional spinal unit shown in Fig. 20 would resolve the problem. Balancing positions in the three-dimensional design correspond exactly with those of the two-dimensional trapezoidal design, producing the same sets of bends and planar movements.

Fig. 20. Three-dimensional spinal unit



A three-dimensional spinal unit or ***link*** is a rigid body made of one piece of plastic. In the adjacent image, parts of the link are given distinct colors. For a joint, the protruding shaft at the head on one link fits into the hollow bearing at the tail of a second link.

Tacks are rigid fins for attachment of movers. A mover, constrained to move in a circle, attaches at one end to the center tack in one link and at the other end to a side tack of the other link. Movers produce a spectrum of bends along circular arcs. Steps between positions in the linear model convert directly to steps between bends. There is no need to adjust j, which is constant, as in the linear design.

Notwithstanding the advantages of the three-dimensional design, this project goes forward with trapezoidal planar versions, where "head" and "tail are reversible conventions and where large exterior movers better delineate the various shapes. This approach is also justified by anticipated improvements. Development of a full three-dimensional design appears to be possible by way of combining two two-dimensional designs, each oriented by gravity, that operate at right angles to each other. Full three-dimensional designs would include new sets of interconnecting movers. Exterior movers appear to be simpler to develop in this fashion.

There also appears to be a development path leading to three-dimensional cylindrical arrays of movers, with longitudinal and circular components similar to those of earthworms. Perhaps, sheathes of elastic materials surround the movers, adding further stabilization. All anticipated developments are based on initial geometrized models that are constrained to move in a two-dimensional plane.

E. A linear construction of rotating joints makes up a spinal assembly and produces collective positions called configurations.

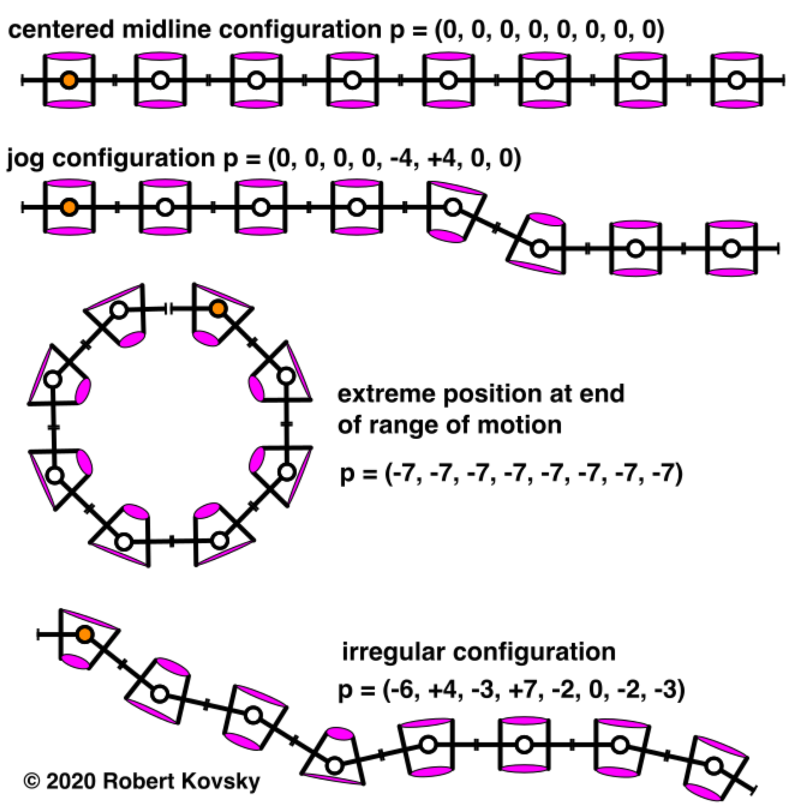
1. A construction with 8 angular joints illustrates classes of spinal assemblies and their configurations.

Spinal joint segments are combined to make up a ***spinal assembly***, a string that has two terminal segments and a number of intermediate segments. One terminal segment is identified as the ***head*** and marked with an orange dot. The head is the first segment; segments are numbered consecutively to the last or tail segment. In figures, the first spinal shaft is often horizontal, directed towards the left.

For purposes of this project, an assembly is made of 8 segments or joints. Each spinal joint operates independently of the other joints and can maintain 15 stationary balancing positions. A particular arrangement of segments is a ***configuration*** of the assembly. In an 8-joint assembly, there are 15^8 distinct configurations (some 2.5 billion) distributed within the range of motion.

A ***configuration vector p*** is defined: $\mathbf{p} = \{b_1, b_2, b_3, b_4, b_5, b_6, b_7, b_8\}$ where each bend $b_i \in \{-7, -6, -5, -4, -3, -2, -1, 0, +1, +2, +3, +4, +5, +6, +7\}$. Looking forward from the head, bends to the left are negative and bends to the right are positive. Configurations and vectors shown in Fig. 21 are illustrative.

Fig. 21. Configurations of spinal assemblies with 8 joints

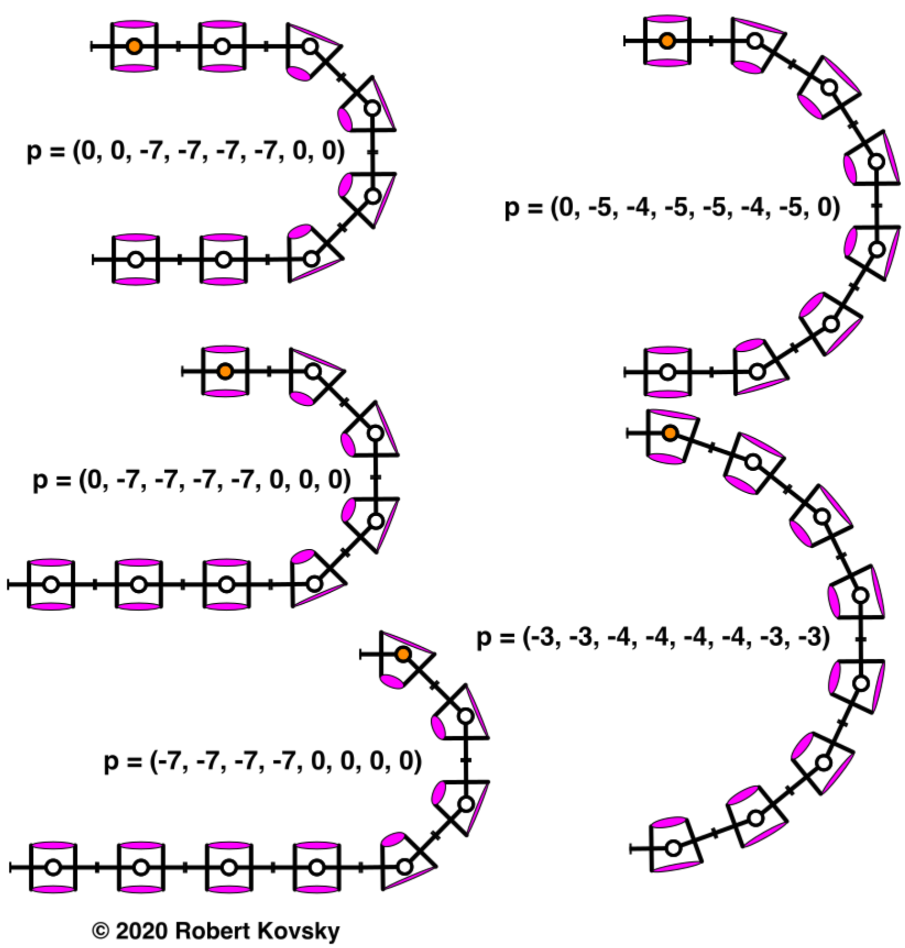


2. A bending measure specifies the curvature of a configuration and defines, e.g., a family of arch configurations.

The ***curvature*** of a configuration is specified by the ***bending measure B***, an angular measure where B = Σb_i or the sum of the bends. Note that – bends cancel + bends. In the figure above, the bending measure of the jog configuration is 0, same as for the centered midline configuration. In the extreme configuration, bending B = –56 arc units. Each arc unit contributes 6.4° to B. Thus, the total curvature of the extreme configuration is 358.4°, almost a full circle.

Fig. 22 shows several configurations where B = –28 arc units and the total curvature of each configuration is 179.2°. A set of configurations, called a ***family,*** can be defined by the condition B = ±28 arc units. This condition is incorporated in the family of arch configurations, used in locomotion scripts constructed below.

Fig. 22. Multiple configurations with the same bending
28 steps of bending or ~ 180°



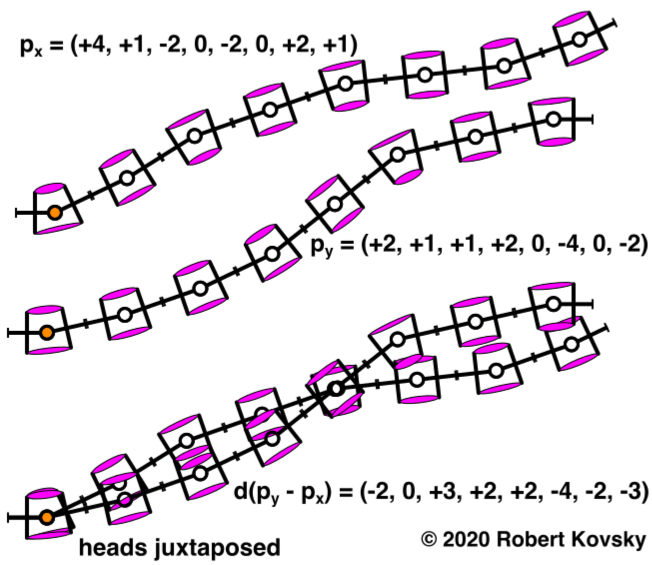
3. Deflections are shifting movements between configurations and provide a basis for comparing configurations.

Fig. 23 shows an illustrative detached shifting movement of an 8-joint spinal assembly. At the beginning of the movement, the configuration is represented by the vector $\mathbf{p_x}$ = (+4, +1, –2, 0, –2, 0, +2, +1). A new set of signals is sent to the spine and the assembly shifts to the new position represented by the configuration vector $\mathbf{p_y}$ = (+2, +1, +1, +2, 0, –4, 0, –2).

Previous definitions of displacements and flexions are extended to configurations of spinal assemblies. A ***deflection*** of the spinal assembly is defined as the difference between the ending vector and the starting vector. That is:

The deflection $\mathbf{d}(\mathbf{p_x}, \mathbf{p_y}) = (p_{y1} - p_{x1}, \dots, p_{y8} - p_{x8})$ is a vector where p_{xm} is the b-index of the mth joint in configuration x and p_{yn} is the b-index of the nth joint of configuration y. In the image below, $\mathbf{d}(\mathbf{p_x}, \mathbf{p_y})$ = (–2, 0, +3, +2, +2, –4, –2, –3).

Fig. 23. A deflection of a spinal assembly



Deflections of the spinal assembly reproduce the detached quasi-static character of displacements of the linear opposing duet. Changed forces cause movements of segments that proceed at different rates depending, e.g., on force differences and positions in the assembly. Segments reach balancing positions at different times. The final configuration does not depend on the initial condition or intermediary factors; this feature is suggestive of the ***equifinality principle*** that has been observed in studies of human movements (Latash at 63-64).

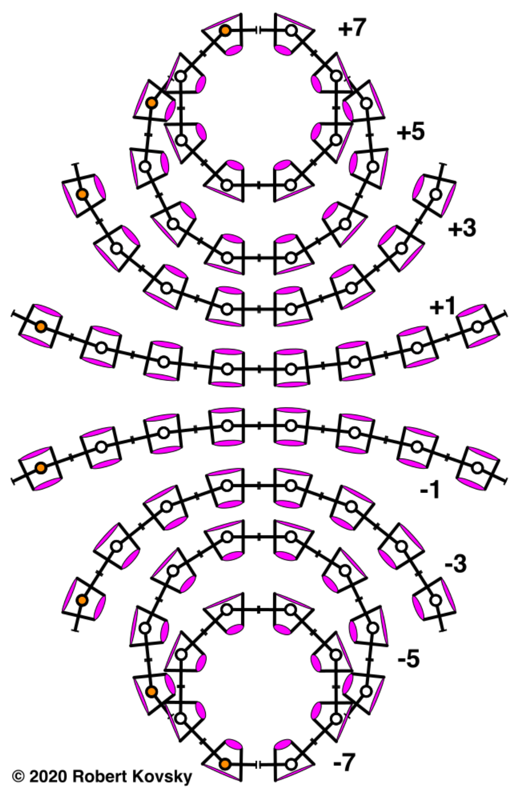
Fig 24 shows odd-numbered members of a family of “regular configurations” (similar to "regular polygons") where all the bends in a configuration are equal.

Extreme deflections are those between **p** = (+7, +7, +7, +7. +7. +7. +7. +7) and **p** = (–7, –7, –7, –7, –7, –7, –7, –7).

One deflection goes from –7 to +7; the other deflection goes from +7 to –7. In one case, **d** = (+14, +14, +14, +14, +14, +14, +14, +14); **d** = (–14, –14, –14, –14, –14, –14, –14, –14) in the other case.

The set of deflections is about twice the size of the set of positions. Operations of two bursters can provide representations for deflections. In such operations, a burst with one pulse represents $d_i = 1$; a burst with 14 pulses represents $d_i = 14$. An absence of pulses can be interpreted as $d_i = 0$ in that segment i holds to a single bend during the deflection.

Fig. 24. Regular configurations



Let **d** = $\mathbf{d_R} + \mathbf{d_L}$, where $\mathbf{d_R}$ denotes flexions to the right, with an increasing b-index that is represented as a “plus” integer from +1 to +14. Similarly, $\mathbf{d_L}$ denotes flexions to the left, with a decreasing b-index represented as a “minus” integer from –1 to –14.

As to the jth segment in a deflecting configuration, a non-zero entry in $\mathbf{d_R}$ means that the corresponding entry in $\mathbf{d_L}$ must be zero because a deflection cannot be both to the right and also to the left. Since joints are independent, flexions can occur in any order without changing results, e.g., all the right flexions at one time and all the left flexions at another time.

A ***mismatch measure*** of a deflection is defined as $w[\mathbf{d}(\mathbf{p},\mathbf{q})] = \Sigma|q_i - p_i|$, with indices p_i, q_i of the two position vectors. The measure, equal to $\Sigma d_{Ri} + |\Sigma d_{Li}|$, measures the total change in bends during a deflection. It also compares two configurations and measures their “mismatch” or, as an opposite measure, their “resemblance.” Two configurations that are identical have a zero mismatch. Two configurations that differ by a small bend in one joint have a close resemblance. If small differences extend to several joints, the resemblance may or may not be close.

F. An augmented spinal assembly performs locomotion movements along a wall that can be represented by scripts.

1. Scripted movements of a spinal assembly are represented by a numerical array resembling a matrix defined in linear algebra.

Using the regular configurations in Fig. 24 as an example, the following array of numbers makes up a script. Each entry specifies the b-index of a spinal segment.

+7	+7	+7	+7	+7	+7	+7	+7
+5	+5	+5	+5	+5	+5	+5	+5
+3	+3	+3	+3	+3	+3	+3	+3
+1	+1	+1	+1	+1	+1	+1	+1
–1	–1	–1	–1	–1	–1	–1	–1
–3	–3	–3	–3	–3	–3	–3	–3
–5	–5	–5	–5	–5	–5	–5	–5
–7	–7	–7	–7	–7	–7	–7	–7

The script describes movements of the spinal assembly. Suppose that the assembly starts in the +7 configuration. Signals arrive and the assembly moves to the +5 configuration. In a detached movement, no further signals arrive until all segments are at rest. When further signals arrive, the assembly proceeds in a similar fashion to the +3 configuration, then likewise to the +1 configuration, the –1 configuration, the –3, the –5 and the –7 configurations, at which point movements cease.

The script can be read from the +7 row to the –7 row or, alternatively, from the –7 row to the +7 row. In the domain of detached movements, scripts are reversible.

Generally, a script is an arrangement of quantities similar to the standard m × n matrix of linear algebra. In such a matrix, an array of numbers is set forth in m rows and n columns. Using standard notation, **A** = $[a_{ij}]$ where a_{ij} is a representative entry, index i runs from 1 to m and index j runs from 1 to n. An example is shown below, a 3 × 5 matrix **A** with integral entries 0–9:

$$\mathbf{A} = \begin{vmatrix} 4 & 5 & 2 & 9 & 5 \\ 2 & 5 & 5 & 0 & 1 \\ 8 & 7 & 3 & 6 & 4 \end{vmatrix} \begin{matrix} \text{and } a_{11}=4;\ a_{12}=5;\ a_{13}=2;\ a_{14}=9;\ a_{15}=5 \\ \text{and } a_{21}=2;\ a_{22}=5;\ a_{23}=5;\ a_{24}=0;\ a_{25}=1 \\ \text{and } a_{31}=8;\ a_{32}=7;\ a_{33}=3;\ a_{34}=6;\ a_{35}=4 \end{matrix}$$

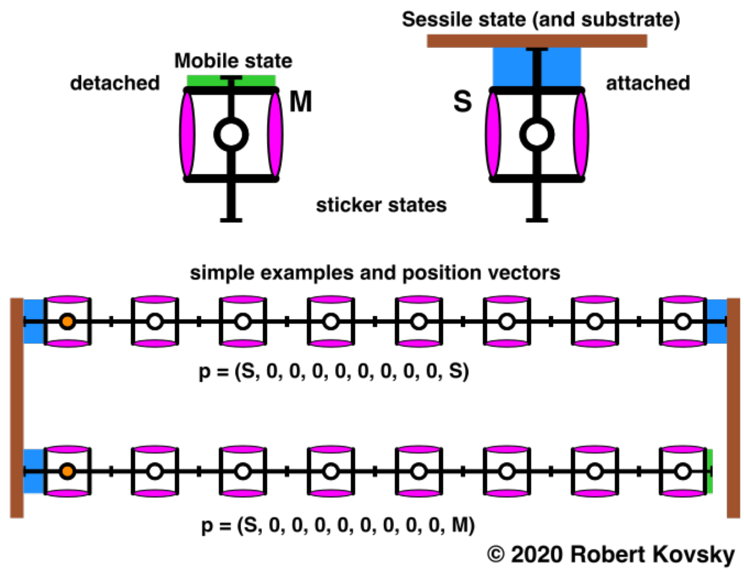
Formally, define **scripts A**, **B**, **C**, …, **X**, **Y**, **Z**… according to the form:
X = $[x_{ij}]$ is a collective entity containing m × n entries. Entries x_{ij} are specified by variables i and j; i ∈{1, …, m} and j ∈ {1, …, n}.

A row in **X** represents a configuration of a spinal assembly and a step between rows represents a detached shifting movement. Movements are reversible.

2. Locomotion along a wall is possible when a mobile spinal assembly is augmented by terminal on/off sticker devices.

In Fig. 25, terminal spinal segments are modified and augmented with ***sticker devices***. A sticker device has two states: (1) a ***mobile*** state (coded **M**) where the sticker is retracted and terminal parts move through water like other body parts; and (2) a ***sessile*** state (coded **S**) where the sticker is extended and the terminal parts have a strong perpendicular attachment to a substrate or wall. Small wobbles are possible but resistance grows rapidly if a wobble is enlarged. The strong attachment pulls the terminal shaft towards a perpendicular orientation during all movements of the spinal assembly, including the most forceful.

Fig. 25. Spinal assemblies augmented with terminal sticker devices



Position vectors **p** are augmented to include 2 new entries denoting **M** or **S** states of the sticker devices. In a new kind of deflection, sticker devices are attached or detached from a wall. Such movements are reversible. The two-wall design in Fig. 25, exactly fits an augmented 8-segment spinal assembly in midline configuration with both sticker devices in a sessile state. Terminal parts must be perpendicular to and a specific distance from the wall for successful attachment.

Fig. 26 shows an application where a mobile sticker device is properly positioned for attachment by means of an ***arch configuration*** where the tail half mirrors the head half and the bending is $B = \Sigma b_i = \pm 28$ arc units or 179.2°. A small wobble in the attachment allows for the 0.8° discrepancy. In other words, during attachment, a sticker device presents its surface to the wall with an offset angle of 0.8°; and it is presumed that the spinal assembly and sticker devices will enter into strong symmetrized attachments at both ends, with small residual internal stresses.

Fig. 26. Bending movements of an augmented spinal assembly with a sessile attachment of the head

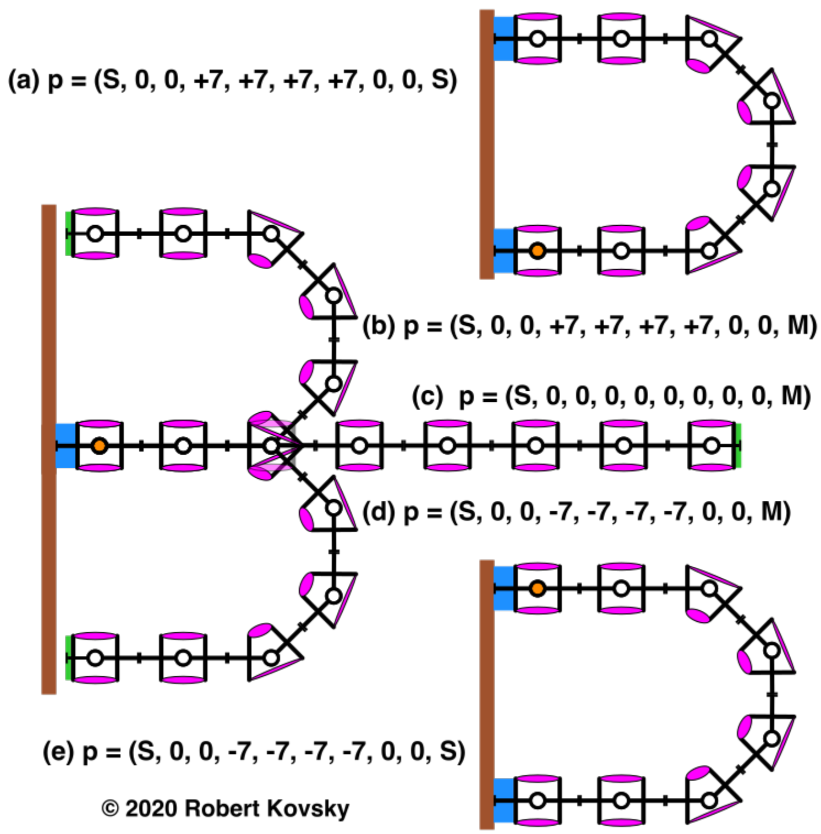
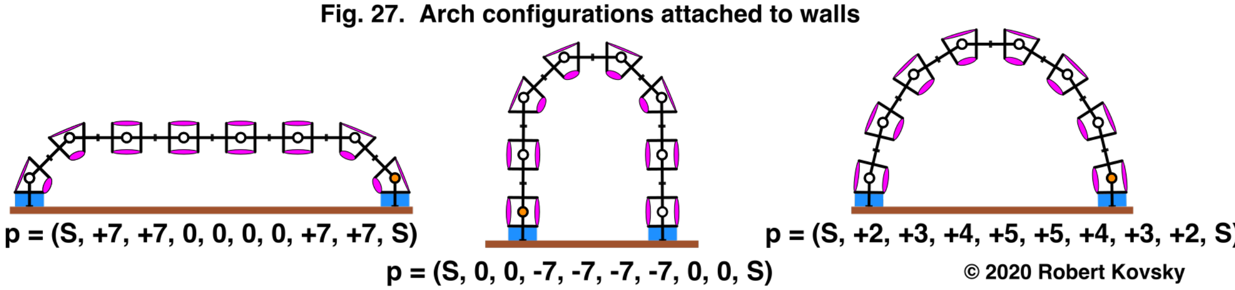


Fig. 26 shows a series of five configurations where the head sticker device, head and first two spinal segments remain fixed throughout. In arch configuration (a), both terminals are sessile; the operative bend is +7. In moving from configuration (a) to configuration (b), the only change is detachment of the sticker device in the tail from the wall. In the next step, the spinal assembly straightens, leading to midline configuration (c). The assembly bends to the other side in the third step, resulting in configuration (d), with the tail end still mobile. The operative bend is –7. In the last step, ending in arch configuration (e), the tail sticker device is attached to the wall; again, both terminals are sessile.

3. Scripts based on seeds for arch configurations represent locomotion movements of an augmented spinal assembly.

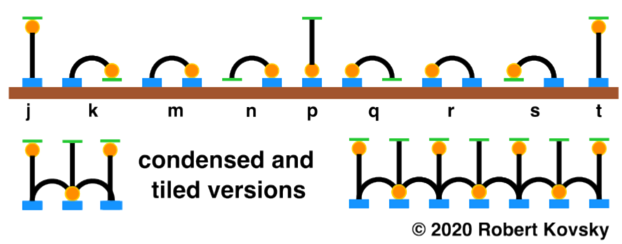
An arch configuration is specified by **p** = (S, a, b, c, d, d, c, b, a, S) where a, b, c and d are b-indices; a+b+c+d = +14 or –14 (depending on orientation); and such b-indices are either all ≤ 0 or all ≥ 0. The 4-tuple (a, b, c, d) is the ***seed*** of the arch configuration. Broad, narrow and mid-range examples are shown in Fig. 27.

Fig. 27. Arch configurations attached to walls



Glyphs are symbolic images of configurations that denote sticker states and spinal orientations while disregarding details of arches. Glyphs for a generic locomotion script are shown below in Fig. 28. Initial and final configurations of the script are identical and the script can repeat, as shown in condensed and tiled versions. A reversed version would show movements to the left.

Fig. 28. Glyphs of configurations for locomotion script



The cycle in Fig. 28 corresponds to a generic ***script for locomotion movements*** of the augmented spinal assembly along a wall, as set forth below; lettered rows of the script (j, k, m, n, p, q, r, s, t) correspond to lettered glyphs. The first configuration is at the top of the script and the last configuration is at the bottom.

j	M	0	0	0	0	0	0	0	0	S
k	M	a	b	c	d	d	c	b	a	S
m	S	a	b	c	d	d	c	b	a	S
n	S	a	b	c	d	d	c	b	a	M
p	S	0	0	0	0	0	0	0	0	M
q	S	w	x	y	z	z	y	x	w	M
r	S	w	x	y	z	z	y	x	w	S
s	M	w	x	y	z	z	y	x	w	S
t	M	0	0	0	0	0	0	0	0	S

Fixed elements 0, M and S are the same in every script. For movement to the right, b-indices satisfy the condition a+b+c+d = +14 and w+x+y+z = –14; for movement to the left, a+b+c+d = –14 and w+x+y+z = +14.

G. In the scriptorium, quadnet devices generate and process scripts and drive remotely-controlled movements of the spinal assembly.

1. Overview of the spinal driver module and its constituent parts: quadnet devices called Loader, Driver, Seeder and Modifier.

Fig. 29 shows the ***spinal driver module*** or ***SDM*** that drives the 8-joint spinal assembly, causing it to perform locomotion scripts. An enlarged version operates in the scriptorium in the head of Wriggler I. The SDM is built around quadnet devices Loader, Driver, Seeder and Modifier, which are arrays of bursters shown in colored blocs. Bursters in a quadnet device operate collectively according to commanding pulses sent by a researcher through projections labeled σ and τ. The researcher specifies the content of a script by setting values of seeds (a, b, c, d) and (w, x, y, z) in the Seeder or by adjusting values of seeds by means of "plus" and "minus" bursters in the Modifier.

Fig. 29. Spinal driver module showing separated layers

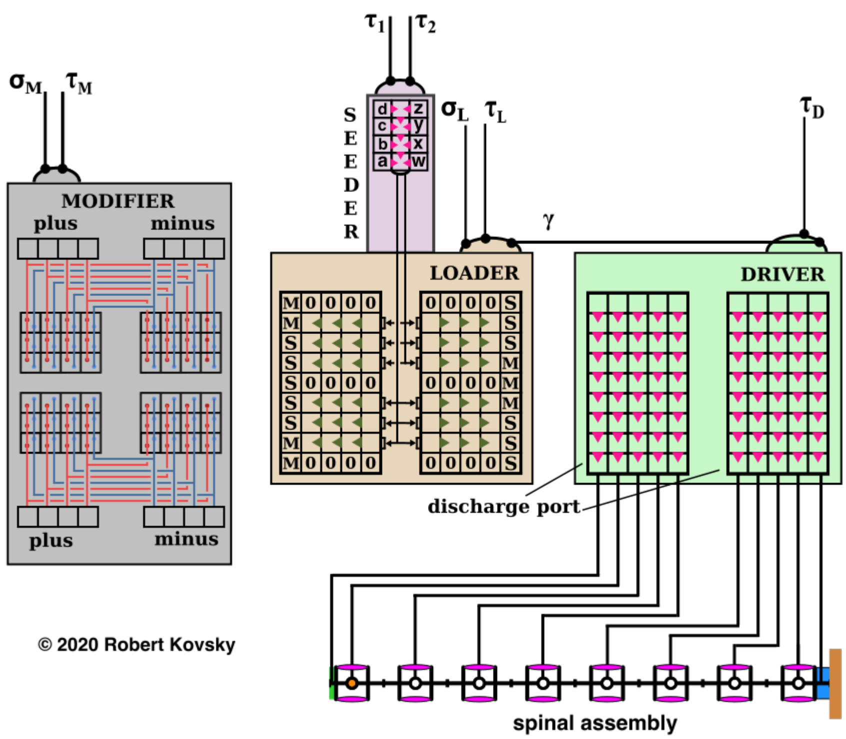


Fig. 29 shows the SDM with its three separate layers spread out. The Seeder is affixed to the Loader. When the SDM is assembled, the Loader fits over the Driver, shrinking the γ projection; each Loader burster fits directly onto a Driver burster, transferring to it either a fixed element in a script (0, M, S) or a variable element based on a seed. The Modifier operates independently and can interact with the Loader, onto which it fits. In § 6 below, the three layers are shown in an assembled version.

Moving up from the spinal assembly, the discharge port in the Driver is made of the bottom row of 10 bursters that holds in readiness the VE settings for the next spinal configuration. (When a whole script is held in a quadnet device, the initial configuration is at the bottom.)

The Driver sends specified pulse bursts to the spinal assembly when triggered by a pulse delivered by the researcher through the τ_D projection to the Driver. For detached shifting movements, the researcher waits until the spinal assembly has come to rest before sending the next τ_D trigger pulse. Initially, the Driver holds V_b and sticker device settings for the whole script; triggered by successive τ_D pulses, the script passes through the Driver in steps, sending successive configuration signals through the discharge port to the spinal assembly.

A whole script is held inside the Loader and transferred to the Driver. Suppose that a script is running in the Driver and that the same or a different script is being held in the Loader. Immediately after the last configuration in the Driver script has been processed through the discharge port, the Driver sends a γ pulse to the Loader, which triggers the transfer of the next script in the Loader to the Driver. Then, processing in the Driver resumes with the re-sending of (M, 0, 0, 0, 0, 0, 0, 0, 0, S).

In one mode of operations, the Loader holds an unchanging script and the SDM repeats that script over and over. In another mode, the Loader is cleared while the Driver is processing a script and the Seeder propagates a new script in the Loader, ready for transfer to the Driver when the next γ pulse arrives.

More scripts are generated in the Modifier. The Loader can transfer seeds of an original script to the Modifier while transferring that script to the Driver. The Modifier later transfers modified seeds back to the Loader after the Loader is cleared. (1) In one mode of operations, the Modifier transfers back seeds for a ***reversed script***, which, if run through the Driver immediately after the original script, returns the spinal assembly to the place on the wall where it was before the original script was run. (2) In another mode, the Modifier transfers back a ***revised script*** that repeats the original script with adjustments to seeds that are made through "plus" and "minus" arrays in the Modifier.

A connected series of movements (a schema) applies to certain anticipated sensory detections and purposes of an engineered organism. An original movement to the right is followed, first, by a reversed movement to the left that returns the organism to the original starting location and, second, by a revised movement to the right which differs from the original movement by adjustments based on detections that occurred during the original movement. This schema recalls the "groping" that has been used to describe rudimentary movements of infants. (Piaget, 395 *et. seq.*)

2. The quadnet device concept.

A plenary quadnet device is an m × n array of uniform elements (devices or modules) that have both independent and collective operations in three layers:

(1) a math-like layer with symbolic operations organized by temporal forms;

(2) a device layer with VES operations based on VE principles;

(3) a body that incorporates the elements and has foundational and variable material properties as to all the operations.

The quadnet concept combines uniform elements in symmetrized arrays, multiple kinds of operations and VES energy conversions — along with capacities for variation and development. The math-like layer and device layer are rational systems explored in this project, which also proposes certain material properties of junctions.

Operations of devices are organized by temporal forms. Although time periods for VE operations are arbitrary, the particular time hierarchy set forth below is provisionally applied to the body and sensorium of Wriggler I. The basis of the hierarchy is a twitch of a force fiber device, which lasts for 5 ticks; a "tick" is a potentially variable period of time. A specific tick of 0.1 sec. produces a twitch of 0.5 sec, which is similar to slow twitches in animals.

0.500 sec	twitch of a force fiber
0.400 sec	one beat in burster operations; slowest pulse period in sensors
0.100 sec	one tick in operations of force devices, movers and bursters
0.020 sec	period between pulses in a burst; fastest pulse period in sensors
0.010 sec	responding period (δ) of a primal timing device
0.001 sec	shortest operational period (e.g., to switch a burster between modes)

Spinal bursters operate according to the foregoing hierarchy in order to drive duets. Devices in a scriptorium are detached from duets and can operate slower or faster. To focus development, it is useful to define a fastest speed by a factor of 10, leading to the following fastest scriptorium time hierarchy:

0.0400 sec	one beat in burster operations; slowest pulse period in sensors
0.0100 sec	one tick in burster operations and junction transfers
0.0020 sec	period between pulses in a burst; fastest pulse period in sensors
0.0010 sec	responding period (δ) of a primal timing device
0.0001 sec	shortest operational period (e.g., to switch a burster between modes)

Movements according to the first hierarchy resemble slow movements of animal bodies; fast operations in the scriptorium are at the fast end of operations in animal brains. These stretches allow for a spreading out of timing intervals in ranges of operations.

To a certain extent, fast operations in the scriptorium can advance ahead of those in the body and ***anticipate*** movements of the body. One line of development aims to generate ***multiple*** different anticipatory movements and then to ***select*** movements that most closely resemble a standard or a form or that appear to be best suited to reach a goal. In proposed processes of Shimmering Sensitivity, such a selection occurs during a critical moment that occurs when patterns of pulses are passing through changes — when many possible movements change into a few selected actual movements. Ultimate aims envision whole-body movements that are selected from large repertoires by means of ongoing waves of Shimmering Sensitivity that arises in networked modules of quadnet devices as they pass through critical moments together.

3. Collectively-triggered operations of bursters in the Loader transfer a whole script to the Driver.

Figure 30 shows a "baby hook-up" of quadnet devices labeled "S," "L," and "D," which are embryonic versions of Seeder, Loader and Driver. These devices ***transfer content*** in the form of a 4-tuple (a, b, c, d) — a seed. In this section, baby transfers lead to transfer of a whole script from the Loader to the Driver. Similar transfer operations between the Loader and the Modifier are discussed in § 6.

In a transfer operation, sending and receiving quadnets have the same m × n size. To start, m × n projections connect corresponding bursters in the two quadnets.

A quadnet device may hold content or it may hold no content. A device that holds no content is ***clear***. Transfer operations require a clear receiving device.

Each 1 × 4 quadnet device in Fig. 30 — **S, L, D** — has a collective operation that is triggered by a pulse through its τ projection. The content in **S** is fixed throughout operations, although changeable by the researcher.

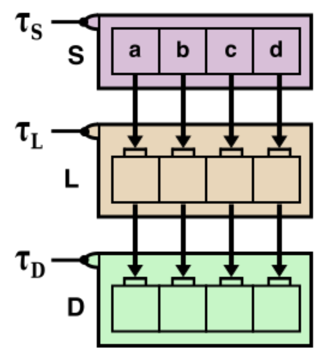
(1) A τ_S pulse to **S** transfers content of **S** to **L** if **L** is clear. If **L** is not clear, its burst receptors are blocked.

(2) If **L** holds content, a τ_L pulse causes **L** bursters to discharge and thus to transfer content to **D** if **D** is clear. Bursters in **L** are cleared automatically after discharge.

(3) If **D** contains content, a τ_D pulse clears **D**.

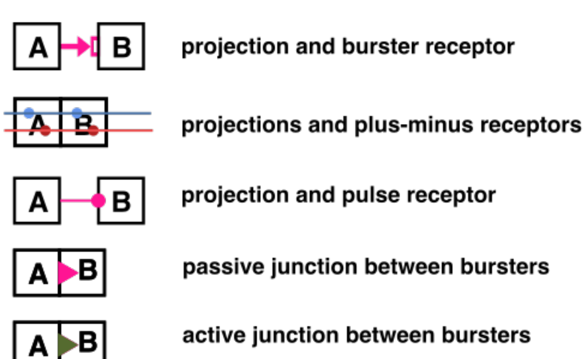
The initial condition is a fixed seed in **S** and clear **L** and **D**. Then, a (τ_S, τ_L, τ_D) cycle can repeat.

Fig. 30. Baby hook-up of quadnet devices for transfers



Parts used in this project include the ***connectors*** shown in color in Fig. 31. Projections carry uniform pulses and operate the same in all uses.

Fig. 31. Connectors used in the project



The ***projection and burster receptor*** unit was developed in prior burster designs.

Similar to burster receptors, ***plus-minus receptors*** are discussed in § 6.

Pulse receptors for timing pulses are discussed in § 4.

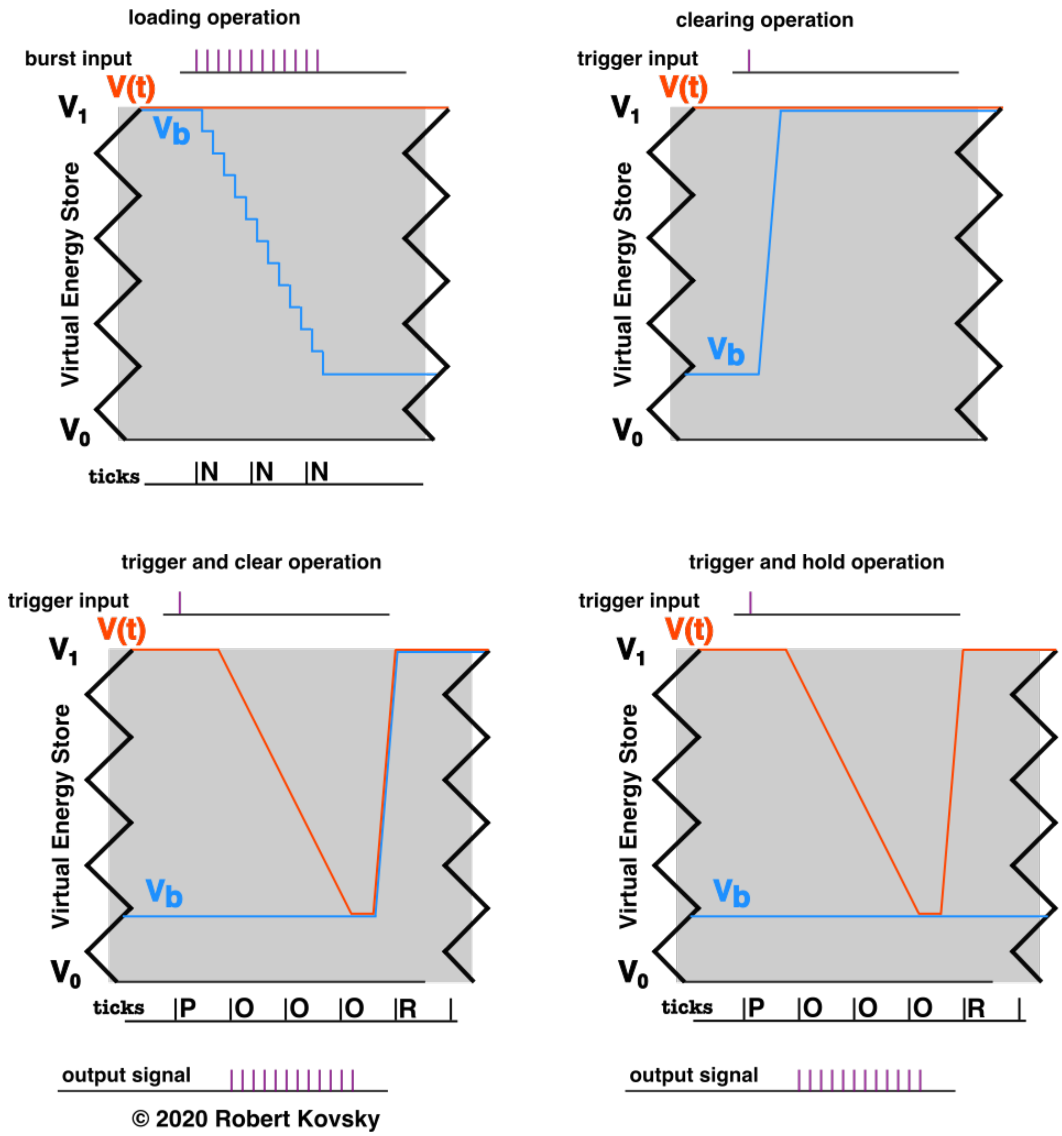
Passive and ***active junctions between bursters*** are developed in this section.

Fig. 32 shows operational schemata for burster devices used in the baby hook-up. These bursters are clear when $V_b = V_1$. V_b is also called "content."

Bursters in the **S** device use the trigger and hold operation. Arrival of a trigger pulse starts the P tick; the output period starts one tick later and lasts for three ticks, followed by a tick for restoration of V(t). V_b is held at a fixed value.

Bursters in the **D** device use two operations, loading and clearing. If **D** is clear, the loading operation starts when a pulse arrives at **D**'s burst receptors, the same as for a repeating burster in § C.1. After **D** has been loaded with content, a trigger pulse clears the device. While **D** is loading, any trigger pulse is blocked.

Fig. 32. VES operations for quadnet bursters



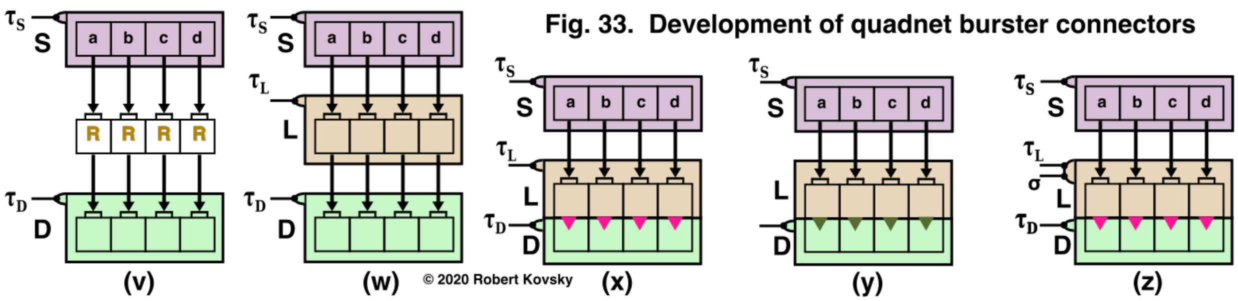
Bursters in the **L** device have two operations, loading and trigger/clear. If **L** is clear, the loading operation runs on arrival of pulses at **L**'s burst receptors in the usual way. If **L** is not clear, burst receptors are blocked.

A trigger pulse to **L** can occur in various cases. (1) In a clear device, the trigger pulse receptor is blocked — only the loading operation will run on a clear device. (2) A trigger pulse arriving after the device has been loaded starts the P tick of the trigger and clear operation. (3) A trigger pulse arriving while the device is being loaded (during the NNN ticks) starts the P tick immediately on completion of the NNN ticks. (4) The trigger pulse receptor is blocked during P, O and R ticks.

Fig. 33 shows a developmental series of connectors. Each **L** design has different operations while those of **S** and **D** remain the same. The baby hook-up, design (w), leads to design (x), which leads to both design (y) and design (z). Designs (x) and (y) illustrate both kinds of junction connectors (passive and active) used in the SDM. Design (z) performs transfer functions of the Loader to the Driver.

Design (v) uses four § C.1 repeating bursters instead of **L**; there is no collective operation. When pulses arrive from **S**, operations of loading, processing, output and clearing occur independently in each R burster in a schema of 8 ticks.

Fig. 33. Development of quadnet burster connectors



In developing the repeating bursters (v) into the baby hook-up (w), collective output and clearing operations are initiated by the external trigger signal over τ_L while the loading operation is maintained in individual bursters.

Development from design (w) to design (x) introduces the ***junction***, which has a conceptual basis that is different from projection/receptor designs. The various designs do not exclude each other; junctions and receptors are used together, e.g., during seed propagation discussed in § 5.

Novelties in junctions are based on a concept of intimacy in shared surfaces between bursters that enables operations more subtle than discharge and receipt of uniform VE pulses. Hypothetically, two bursters with a shared surface have a conjugal relationship that can incorporate "something" like a yin/yang duality of mutual interactivity. Here, the "something" is limited to math-like definitions of interactions between bursters.

(1) What is transferred through an **L-D** junction – during a loading operation between L_i and D_i – is the device setting V_b of the L_i device, namely, the stop-discharge point of burster operations. In such a transfer, the starting $V_b = V_1$ value of the clear D_i burster is changed to match the V_b value of the L_i burster.

The two kinds of transfers (through projections or junctions) have identical results as to operations of **D**. By means of a junction, V_b is transferred directly instead of indirectly by means of pulses.

An idealized change in V_b does not require VE. In another version, 1! of VE is required for a change, regardless of the values of V_b. A new 1! VES is added to the device to fuel the V_b change; R is increased by 1!/tick to keep it full.

(2) As with projections, transfer of content from **L** to **D** in the passive junction of design (x) is triggered by a τ_L pulse. However, a sending burster does not attempt to transfer content through a junction unless the receiving burster is clear. In the projection version of trigger/clear operations, the sending burster clears regardless of whether the receiving burster is clear or blocked. If the receiving burster is blocked, the transfer fails and the content is lost.

In the junction version of a transfer, in contrast, the sending burster clears only if the transfer has been completed. There are no failed transfers through a junction. In other words, the sending burster detects the readiness (clear or blocked status) of the receiving burster through the junction surface and the sender's operations depend on that status – a feature of ***sender sensitivity***.

The feature of sender sensitivity in the passive junction is further developed for the active junction in design (y): transfer of content from **L** to **D** is caused by the clear condition of **D** rather than by a τ_L pulse, as in the (x) version. If both **L** and **D** are clear, **L** automatically transfers content to **D** as soon as **L** receives such content. If both **L** and **D** hold content, clearing **D** leads automatically to a transfer from **L** to **D** and a clearing of **L**. In design (y), there is no use for a collective trigger pulse τ_L.

Further development is needed to operate the Driver and drive the SDM. As discussed in § 1, the Loader can alternatively hold a script or receive a different script after clearing. Therefore, the **L** device in design (x) is developed into design (z) where bursters follow the trigger/hold schema (instead of trigger/clear) and a collective clearing operation is separately caused by a σ pulse.

Design (z) is readily enlarged into the design for the Loader that transfers a whole script to the Driver. Loader and Driver each have a 9 × 10 array of bursters and there are 9 × 10 passive junctions; each transfers content from a Loader burster to the corresponding Driver burster. As in the 1 × 4 hookup, transfer operations in Loader bursters follow the trigger/hold schema with a separate clearing operation.

A whole script is transferred in a single operation. Collective transfer is triggered by a τ pulse — or by a γ pulse that is sent to the Loader when the Driver is clear, as discussed below. A script held in the Loader can be transferred to the Driver repeatedly.

A pulse through the σ_L projection clears seed content from the Loader without disturbing the fixed parts (0, M, S) of a script. Then, new seed content can be pre-loaded from the Seeder or Modifier as discussed below.

4. Sequentially-triggered transfers of content inside the Driver produce a scripted series of spinal configurations.

Fig. 34 shows a design for a reduced driver column. The full Driver device has an enlarged version. Operations in any column in the Driver occur independently of those in other columns, so one representative column is sufficient. A reduced column holds 1 seed value in 5 bursters and processing requires 10 steps; a full column holds 2 seed values in 9 bursters and processing requires 18 steps. Enlargement of the reduced driver column to the full Driver is direct.

Fig. 34. Reduced driver column

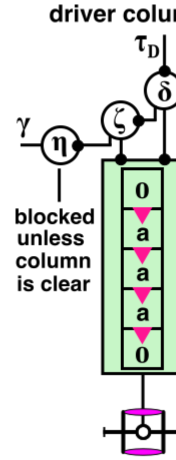
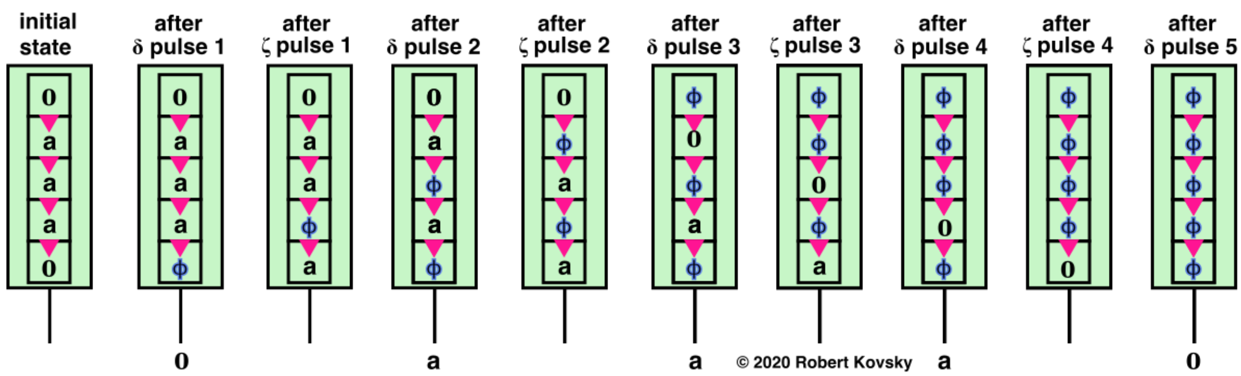


Fig. 34 shows timing devices δ, ζ and η that process trigger pulses. Suppose that a trigger pulse through τ_D arrives at timing device δ at time t_0. Then, at time $t_0 + \delta$, timing device δ discharges pulses through two projections; one pulse triggers the column and the other pulse travels to timing device ζ. Next, ζ discharges two pulses at time $t_0 + \delta + \zeta$; one pulse triggers the column and the other pulse travels to timing device η for possible production of a γ pulse.

The timing interval δ is short in comparison to that of ζ. Perhaps $\delta = 0.1$ tick and $\zeta = 10$ ticks. Thus, triggers come in pairs. A first trigger at time $t_0 + \delta$ starts a ***discharge step*** that changes movers in the spinal assembly along with V_b values of bursters in the column; the second trigger at time $t_0 + \delta + \zeta$ starts a ***preparation step*** that changes V_b values in bursters in the column but does not affect the spine.

Fig. 35 shows a progression of V_b values through a reduced column of bursters as a result of trigger pulses. Bursters use the trigger/clear schema; transfer of V_b through a junction and clearing of the sending burster occur only if the receiving burster is clear. The content of a clear burster is denoted by φ.

Fig. 35. Progression of V_b values through a reduced driver column



The initial state represents the content after loading. In the first discharge step, the first τ_D pulse causes the discharge port burster to send a pulse burst to its spinal segment for the midline position (b=0, n=8). The discharge port burster is cleared. No other burster can discharge and other V_b values in the column stay the same.

The first τ_D pulse also causes the first preparation step after a delay of ζ; the V_b value "a" advances to the discharge port, leaving a cleared burster behind it.

The second τ_D pulse causes the second discharge step – the discharge port sends the pulse burst for the "a" setting and clears. The burster cleared in the prior step is provided content by the burster behind it, which then clears. There are therefore two cleared bursters that receive content during the second preparatory step.

The third τ_D pulse causes the third discharge step, creating three cleared bursters; again, contents are advanced in the preparatory step. The fourth τ_D pulse continues the process, leaving four cleared bursters and the final value 0 ready for discharge.

The discharge step caused by the fifth τ_D pulse sends the final value 0 to the spinal element. Now the column is entirely clear. When the fifth preparatory pulse from the ζ timing device arrives at the η timing device, that device is responsive for the first time, discharging a γ pulse. In the full SDM, the γ pulse travels to the Loader and possibly causes the transfer of the next script to the Driver.

5. Scripts are generated from seeds of arch configurations that are held in the Seeder and propagated through the Loader.

Fig. 36 shows a design for propagation of the seed (a, b, c, d) through the Loader. The design is reduced from the Loader in the full SDM to just the lower left-hand quadrant, which holds the first five configurations of the head half of the spinal assembly. The enlarged full Loader follows directly by adding a mirrored version for the tail half of the spinal assembly and a cloned version of both head and tail in the upper Loader array, which is used in propagation of the second seed (w, x, y, z).

Bursters in the Loader with fixed values (O, S, M) follow the trigger/hold schema as discussed above; the same V_b values are sent in every transfer to the Driver. Variable bursters in the Loader follow (1) the trigger/hold schema during external transfer operations that use passive junctions and (2) the trigger/clear schema during internal seed propagations that use active junctions.

Prior to seeding, the researcher has cleared the Loader with a σ_L pulse and prepared the Seeder with (a, b, c, d). As before, seed values are defined by levels of V_b in bursters. Seeder bursters holding prepared seed values use the trigger/hold schema; bursters in the central column use the trigger/clear schema.

A trigger pulse τ_1 propagates the seed (a, b, c, d). In the reduced design, only the τ_1 pulse is operative. A trigger pulse τ_2 would propagate the seed (w, x, y, z).

A τ_1 pulse to the Seeder causes the (a, b, c, d) bursters to send their content into the central column. It also starts automatically repetitive trigger operations in the central column that continue until that column is clear. The progression of content through the central column is follows that of the Driver design.

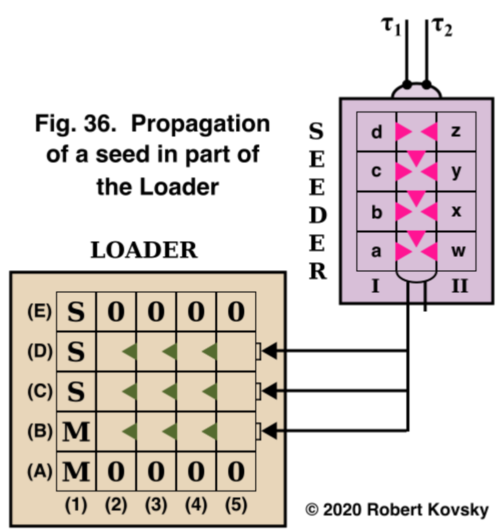


Fig. 36. Propagation of a seed in part of the Loader

When the Seeder sends the first "V_b = a" content through projections, bursts arrive at the three seed bursters in column (5) of the Loader. Bursters in column (5) automatically transfer such content to bursters in column (4) through active junctions and then clear.

Continuing, bursters in column (4) transfer the content to column (3) and clear. Next, the content transfers to column (2), leaving columns (3), (4) and (5) clear.

Next, the Seeder sends "b" content to column (5) of the Loader and that content is transferred until it ends up in column (3). Similar operations complete the propagation of "c" content and "d" content.

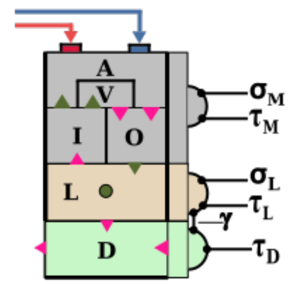
6. The Modifier receives seeds of a script from the Loader and can transfer back to the Loader seeds for a reversed script (that returns the spinal assembly to the original location) or adjusted seeds for a revised script.

Fig. 37 shows the three layers of the SDM in a sectional module that includes all the connectors and controls for representative bursters in the Loader, Driver and Modifier; the gray Modifier is a module made of four bursters (**I**, **A**, **V** and **O**).

The sectional arrangement in Fig. 37 is replicated in seeded areas of the SDM. Collective operations (σ, τ) apply to the entire quadnet device and thus to representatives in the section.

As previously discussed, pink passive junctions operate between the Loader and the Driver and internally in the Driver. The green dot in the **L** burster represents active junctions that connect columns inside the Loader during seeding operations.

Fig. 37. Section of spinal driver module



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The Modifier module has four bursters called **I**nput, **O**utput, Reversal (**V**) and **A**djustment. The Modifier has the following collective commands.

(1) A τ_M pulse (without a σ_M pulse) clears all Modifier bursters and prepares the Modifier for receipt of fresh content from the Loader.

(2) A σ_M pulse is followed by a τ_M burst with one or two pulses in the burst: a burst with one τ_M pulse triggers transfer of content from **V** to **O**; a burst with two τ_M pulses triggers transfer of content from **A** to **O**. Content in **O** is automatically transferred to **L** through the active junction.

If **I** is clear, a τ_L pulse transfers content from **L** to **I**. **I** bursters use a trigger/hold schema, holding content after automatic transfer to **A** and **V**. **I**, **V** and **A** can hold content for an indefinite period. Then, a σ_M pulse followed by a τ_M burst triggers transfer of content from either **A** or **V**, which passes first to **O** and then to **L**.

The Reversal burster **V** operates like the inverter **I** in § C.2 except that the capacity of the VES of **V** is 16! rather than 15!. Interpreted as pulses, the schema is "k pulses in, 16-k pulses out" instead of the 15-k version in the § C.2 version. When a **V** burster is clear, $V_1 - V_b = 16!$.

By means of burster **V**, a b-index is changed into its negative. If the original value in the **L** burster is $V_1 - V_b = 3!$ the result in **V** is $V_1 - V_b = 13!$ in **V**; thus, b = –5 in **L** becomes b = +5 in **V** and **O**, which is subsequently returned to **L**. An input burst of 8 pulses (V_b =8!) becomes an output burst of 8 pulses, 0 to 0, midline to midline.

In the following locomotion script for movements to the right, the widest arch in the repertoire is first (at the top); the narrowest arch is second.

M	0	0	0	0	0	0	0	0	S
M	+7	+7	0	0	0	0	+7	+7	S
S	+7	+7	0	0	0	0	+7	+7	S
S	+7	+7	0	0	0	0	+7	+7	M
S	0	0	0	0	0	0	0	0	M
S	0	0	–7	–7	–7	–7	0	0	M
S	0	0	–7	–7	–7	–7	0	0	S
M	0	0	–7	–7	–7	–7	0	0	S
M	0	0	0	0	0	0	0	0	S

After performance of movements to the right in the above script, the script below represents reversed movements to the left: if the original script above in **L** is transferred to **V**, the script below is the ***reversal script*** that is transferred back to **L**. There is a "reversal" such that running the reversal script after the original script returns the spinal assembly to the place on the wall where it was before the original script. As in the original script, the widest step in the repertoire is first and it is again followed by the narrowest step — in other words, the reversed movement is not a "time-reversed" movement – not like running a film backwards.

M	0	0	0	0	0	0	0	0	S
M	–7	–7	0	0	0	0	–7	–7	S
S	–7	–7	0	0	0	0	–7	–7	S
S	–7	–7	0	0	0	0	–7	–7	M
S	0	0	0	0	0	0	0	0	M
S	0	0	+7	+7	+7	+7	0	0	M
S	0	0	+7	+7	+7	+7	0	0	S
M	0	0	+7	+7	+7	+7	0	0	S
M	0	0	0	0	0	0	0	0	S

The Adjustment burster **A** also receives V_b content originating from an **L** burster. Between receipt and discharge into Output burster **O**, Adjustment content can be changed by pulse bursts sent by the researcher to plus-minus receptors.

Pulses through the plus receptor lower the level of V_b in the **A** burster step by step, increasing the number of output pulses; pulses through the minus receptor raise the V_b level. Plus-minus adjustments resemble deflections discussed in § E.3. An **A** burster that receives a plus adjustment does not receive a minus adjustment and vice-versa. Because the total curvature of an arch remains constant, the total sum of plus adjustments equals that of minus adjustments. Adjustments push forward or pull back the span of an arch and manifest math-like features.

References

Richard C. Brusca and Gary J. Brusca, with illustrations by Nancy J. Haver, Invertebrates, 1990.

John Hertz, Anders Krogh and Richard Palmer, Introduction to the Theory of Neural Computation, 1991.

William James, The Principles of Psychology, 1890.

Mark L. Latash, Fundamentals of Motor Control, 2012.

Jean Piaget, The Origins of Intelligence in Children, 1936.

C. Truesdell, Rational Thermodynamics, 2d ed. 1984.

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