Until about 1900 the word *torpedo* referred to a static naval mine. However, the modern mobile weapon came into being in the 1870s and became a significant factor in naval warfare by the last decade of the 19th century. At that time an Irish-Australian engineer named Louis Brennan developed a torpedo for the British Royal Navy. The Brennan torpedo was deemed less suitable than the then-dominant Whitehead torpedo for use aboard ships because it was wire guided, but it was accepted for coastal defense, launched from land [1]. For a brief summary of early torpedo development, see “Early Torpedoes.”

The trajectories of early torpedoes were haphazard, and these devices came to be controlled in bearing and depth by mechanical sensors. Initially these sensors took a wide variety of forms before the 1898 introduction of reliable gyroscopes. Gyros have dominated the field ever since, such is their utility. From a control engineering perspective it is interesting to consider the earlier contenders, which displayed great ingenuity. The Brennan torpedo, shown in Figure 1, was provided with, we believe, a tangential flyball governor. We cannot be certain because of the secrecy that surrounded the guidance system of this innovative torpedo, but the documentary evidence and the theoretical considerations presented in this article support this conjecture. In fact, a key member of Brennan’s team later presented a paper on the subject of flyball governors, in which he discussed the torpedo hunting problem. The speculation concerning the role of tangential governors arose from our interpretation of this paper. See “Depths of Secrecy.”

PLUMBING THE DEPTHS

Since the Brennan torpedo was wire-guided, it did not need a bearing-direction control mechanism, as required by other torpedoes that were autonomous after launch. However, wire guidance was unable to control torpedo depth, and thus the Brennan torpedo suffered from a problem that plagued other torpedo designs from this period, that is, it tended to “porpoise.” Torpedoes were designed to travel beneath the surface at a constant depth, typically 10 ft, but in practice their depth oscillated sinusoidally, with a wavelength of approximately 200 yd. Because the oscillation amplitude could be as much as 20 ft, the torpedo might pass underneath its intended target.

Robert Whitehead developed the first successful torpedo and the first successful depth-control mechanism. His “secret” was a pendulum-and-hydrostat controller, whose operation is explained below. The sinusoidal oscillation of torpedo depth is an example of *hunting*, in which a feedback mechanism responds sluggishly to an unwanted deviation, resulting in an oscillation about the desired depth. This hunting behavior occurred in earlier designs because the controller, a simple hydrostat, responded only to the amplitude of the variation. Whitehead’s device responded also to the rate of change, that is, the derivative, of amplitude, which more quickly corrected deviations from the desired depth. Brennan’s solution also responded to both amplitude and its derivative, and worked well. In this article we show why, in the author’s opinion, the Brennan solution was a tangential governor, why such devices work well, and in particular why it works better than its better-known cousin, the centrifugal governor. We do not know what the Brennan solution was, because his design was shrouded in secrecy and no Brennan torpedo exists intact. The goal of this article is to compare the performance of the tangential governor with that of the more familiar and contemporary centrifugal governor. We show that the tangential governor is less prone to hunting and thus is a more suitable candidate for the Brennan torpedo’s depth controller.

FLYBALL GOVERNORS

The familiar steam-engine centrifugal governor is shown in Figure 2(a), (c). Under steady conditions, the angular
speed of the engine shaft AB determines the angle of the flyball arms CD and EF. These swinging arms are connected to the shaft by the horizontal arms DE, which are fixed to the shaft. The additional linkage GHJK connected to the swinging arms causes the sleeve HJ to slide up or down as the shaft angular speed varies. The sleeve is connected to the steam engine’s throttle valve, not shown in Figure 2. The flyball angle thus depends on the shaft angular speed, and the linkage is such that the throttle valve tends to open when the angular speed is too low and close when it is too high. Therefore, the centrifugal governor acts as an angular speed regulator by...
Depths of Secrecy

Mobile torpedoes largely replaced static mines in undersea warfare, from about 1870, and changed the nature of maritime warfare. It is no surprise, therefore, to learn that great secrecy surrounded the guidance systems of these new-fangled weapons. The guidance systems were crucial to torpedo accuracy and played a significant role in determining the maximum effective range of the weapons. Whitehead switched his torpedoes over to a gyro system in 1898, ensuring directional stability. That is, the vertical rudder controlling azimuth direction would be under the control of a gyro. Earlier gyros were insufficiently well engineered, and thus other devices were used, such as the pendulum system alluded to in “Early torpedoes.”

To control torpedo depth, Whitehead invented his famous “secret.” The oxymoron is apt because it was well known that Whitehead had developed an effective depth controller and that he kept its design a closely guarded secret. The secret was a commercial matter; Whitehead never patented his pendulum-and-hydrostat controller, an early proportional-derivative device. The Whitehead device apparently worked quite well and solved the “porpoising” problem, which plagued early torpedoes. The amplitude of the sinusoidal trajectory was reduced from tens of feet to a few inches [S5].

Brennan solved the porpoising problem differently with, we believe, a tangential flyball governor. We do not know for sure what system was used, because the depth-control mechanism was subjected to great secrecy. This mechanism was manufactured by separate teams of workers who knew only about part of the mechanism. The completed device was fitted into two sealed metal containers, which were placed in the torpedoes just prior to use. At other times the sealed containers were locked in different safes; both keyholders had to be present to unlock the safes and install the sealed boxes into the torpedoes immediately prior to use [S6].

The idea for the Brennan torpedo depth controller probably came from Prof. William C. Kernot of Melbourne University, Australia, who worked with Brennan and who later read a paper to the Victorian Institute of Engineers in Melbourne. The paper does not state the detailed mechanism and indeed is ambiguous on several points. The paper is quoted at length in [S6]. It does hint that a governor mechanism was used for depth control of the Brennan torpedo and points out the advantages of a tangential governor. At first reading it seems that a combination of centrifugal and tangential governors is used, “taking cognisance of both speed and acceleration.” Such a mechanism would be clumsy, Kernot admits, and a more careful reading of his paper shows that he appreciated the capability of a carefully designed tangential governor on its own to measure both angular speed and angular acceleration. On the other hand, it is possible that the good professor was discussing the tangential governor simply as an analogy to the Brennan torpedo guidance system, which required measurement of torpedo depth and rate of change of depth. We cannot tell from his writings; the secrecy surrounding Brennan torpedo depth control is such that we can only speculate.


providing a control signal that is proportional to shaft angular speed.

Speed regulation was important for many applications of the steam engine during the Industrial Revolution. In fact, however, the centrifugal governors of mid-19th century steam engines did not work as well as those of earlier, less-well-engineered machines. The newer engines exhibited hunting behavior, unlike the earlier machines, and this counterintuitive development was a costly puzzle until it was solved independently in the 1860s and 1870s by the Scottish physicist James Clerk Maxwell and the Russian engineer J. Vyshnegradskii. Both scientists derived conditions that must hold if the centrifugal governor action is stable, and subsequent steam engines performed much better once the Maxwell/Vyshnegradskii conditions were understood and acted on by steam-engine designers [2], [3, pp. 213–220].

We believe that the Brennan torpedo depth regulator may have been a tangential governor, shown in Figure 2(b), (d). In this case, the swinging arms are not permitted to move radially toward or away from the rotating shaft, but instead they move tangentially, as indicated in the figure. A control engineer today would recognize that the centrifugal governor is sensitive to shaft angular speed, whereas the tangential governor is sensitive to shaft angular acceleration. In particular, if the shaft angular speed is constant, then the tangential governor produces a zero signal. In fact, the tangential governor is sensitive to both shaft angular speed and angular acceleration, as shown in the next section. The sensitivity to angular acceleration in addition to angular speed made the tangential governor more responsive than the centrifugal governor since it provides a control signal that is both proportional and derivative in terms of angular speed. Consequently, compared to the centrifugal governor, this sensor provides control that is stable over a wider range of operating parameters and reaches equilibrium more quickly when disturbed. Reports written about the Brennan torpedo guidance system indicate that this fact was appreciated at the time of the torpedo design. In fact, the idea of tangential governors is as old as that of centrifugal governors. One of the first references to tangential
A solution to the torpedo depth control problem that avoids hunting requires sensitivity to both depth and derivative of depth, such that the control system applies two independent adjustments to the horizontal rudder. Whitehead’s “secret” mechanism for depth control involved measurements of water pressure and torpedo pitch angle, that is, longitudinal slope. A pressure-sensitive diaphragm measured torpedo depth and actuated the torpedo’s horizontal rudder if the depth was not right. A pendulum sensitive to torpedo pitch measured the rate of change of depth and independently actuated the rudder if this rate of change was not right. Thus, if a torpedo is at too great a depth but is rising, then the actions on the horizontal rudder by the two feedback components, namely, the diaphragm and the pendulum, cancel each other, which is the correct response because the torpedo is heading toward the correct depth. If the torpedo is too deep and descending, then the actions of the two components add, causing a horizontal rudder change that brings the torpedo back toward the correct depth. Similarly, the feedback component actions cancel if the torpedo is too high but falling, and they add if the torpedo is too high and rising.

Perhaps the Brennan torpedo depth control problem was solved in a similar way, derived independently; that is, the Brennan team came up with an almost identical solution to that of the Whitehead torpedo designers. An initial reading of the available literature suggests that this is the case and indeed is the most likely scenario. However, the control mechanism’s response to depth, as well as to derivative of depth, is strongly reminiscent of the tangential governor’s sensitivity to steam-engine shaft angular speed and acceleration. The designer of the Brennan torpedo guidance system enthusiastically discussed the merits of this governor, comparing it with the diaphragm-and-pendulum torpedo guidance system. Consequently, it appears likely that the secret solution applied to the Brennan torpedo depth control involved a tangential governor.

For a tangential governor to operate based on shaft rotation, a shaft angular speed must vary with torpedo depth, but we do not know if this was the case. However, it is easy to imagine, if not implement, ways in which this dependence can be realized. For example, a depth-sensitive diaphragm may be linked to a clutch, which influences the rotation rate of an auxiliary shaft whose angular speed and acceleration are monitored by a tangential governor. Henceforth we assume that the Brennan torpedo depth is maintained by a tangential governor that senses the angular motion of an auxiliary shaft and drives the horizontal rudder. Let us see how such a governor performs.

**ANALYSIS OF THE TANGENTIAL GOVERNOR**

A diagram of the tangential governor that defines notation is provided in Figure 3. We adopt a coordinate system centered on the point of intersection of the rotating auxiliary shaft and the horizontal arms, as shown. The flyballs are at positions \((x, y, z)\) and \((-x, -y, z)\), where

\[
x = d \cos(\psi) + l \sin(\theta) \sin(\psi), \\
y = -d \sin(\psi) + l \sin(\theta) \cos(\psi), \\
z = -l \cos(\theta). \\
\]

Note that \(x^2 + y^2 + z^2 = d^2 + l^2\), as expected. The speed of each flyball is \(\dot{v}\), where \(\dot{v}^2 = \dot{x}^2 + \dot{y}^2 + \dot{z}^2\), where a dot indicates time derivative. The kinetic energy of the flyball system is thus

\[
T = md^2 \dot{\omega}^2 + ml^2 \dot{\theta}^2 + ml^2 \omega^2 \sin^2(\theta) - 2 ml d \dot{\theta} \cos(\theta),
\]

where \(\omega = \dot{\psi}\). The potential energy is

\[
V = -2ml \dot{\theta} \cos(\theta).
\]
The Lagrangian $L = T - V$ can be rewritten as $L = T_{eff} - V_{eff}$, where $V_{eff}$ is the effective potential [6, p. 64]. The effective potential contains all of the terms that are independent of $\theta$ and thus depends only on position. In particular,

$$T_{eff} = ml \dot{\theta}^2 + ml \dot{\theta}^2 - 2mla\dot{\theta} \cos(\theta)$$

(6)

and

$$V_{eff}(\theta) = -2mgl \cos(\theta) - ml \dot{\theta}^2 \sin^2(\theta),$$

(7)

which is plotted in Figure 4. Note that there is an unstable equilibrium at $\theta = 0^\circ$ as well as a stable equilibrium at a higher flyball angle, which depends on the auxiliary shaft angular speed $\omega$.

The Euler-Lagrange equations $\partial L / \partial \dot{\theta} = (d/dt)(\partial L / \partial \dot{\theta})$ yield the equation of motion

$$\dot{\theta} + \left(\frac{g}{l} - \omega^2 \cos(\theta)\right) \sin(\theta) + \frac{b}{m} \dot{\theta} = \frac{d}{I} \cos(\theta).$$

(8)

Since the Euler-Lagrange equation does not account for dissipation, we include the friction term $b \dot{\theta}/m$. Equation (8) represents the action of the auxiliary shaft on the governor through the terms proportional to $\omega^2$ and $\dot{\omega}$, so that the governor is sensitive to both angular speed and angular acceleration. Note that, unlike the conventional centrifugal flyball governor equation of motion [2, (3)] (8) depends on the axle angular acceleration $\dot{\omega}$.

From (8) we obtain the equilibrium condition

$$\left(\frac{g}{l} - \omega^2 \cos(\theta_0)\right) \sin(\theta_0) = 0.$$

(9)

Consequently, there are equilibrium angles $\theta_0 = 0$ and $\cos(\theta_0) = g/l \omega_0^2$, corresponding to the minimum potential of (7) as shown in Figure 4. From (9) and Figure 4 we see that stability of the tangential flyballs depends on the auxiliary shaft angular speed in the following way. First, if angular speed is less than $\sqrt{g/l}$, then a stable equilibrium occurs at the flyball angle $\theta_0 = 0$. Furthermore, for higher angular speeds, $\theta_0 = 0$ corresponds to an unstable equilibrium. Finally, a stable equilibrium occurs for $\theta_0 = \cos^{-1}(g/l \omega_0^2)$.

The phase portrait for the tangential flyball is more complex than that of the conventional centrifugal governor, which exhibits no such change in stability with angular speed at $\theta_0 = 0$.

Regarding the influence of flyball position on auxiliary shaft angular speed, this effect is assumed to be analogous to the steam-engine centrifugal governor. Thus,

$$\dot{\omega} = \Gamma [h(\theta) - h(\theta_0)].$$

(10)

The function $h(\theta)$ is flyball height, which, through a linkage, drives the horizontal rudder. The constant of proportionality $\Gamma$, which converts flyball height into auxiliary shaft acceleration, depends on the linkage, that is, how the governor controls the horizontal rudders.
The flyball of Figure 3 satisfies
\[ h(\theta) = l \cos(\theta). \]  

Equations (8) and (10) represent the system consisting of the auxiliary shaft and the tangential governor, where (8) describes the influence of auxiliary shaft angular speed and angular acceleration on the tangential flyball angle, while (10) describes the influence of the flyball angle on auxiliary shaft angular speed, through rudder regulation. The question we wish to answer is the following: What conditions must apply for this hypothetical depth-control system, closely analogous to a steam engine governor system, to operate in a stable manner? To answer this question, we perform the same type of linearization that Maxwell applied to the original centrifugal governor in 1868.

STABILITY CRITERIA

We assume that the system deviates from equilibrium by perturbations given by
\[ \theta = \theta_0 + \Delta \theta, \]  
\[ \omega = \omega_0 + \Delta \omega \]

and substitute into the equations of motion, neglecting terms that are quadratic. From (8)–(13) we obtain
\[ \Delta \ddot{\theta} + \frac{b}{m} \Delta \dot{\theta} + \omega_0^2 \sin^2(\theta_0) \Delta \theta = 2\omega_0 \sin(\theta_0) \cos(\theta_0) \Delta \omega + \frac{d}{l} \cos(\theta_0) \Delta \dot{\omega}, \]  
\[ \Delta \dot{\omega} = \Gamma \dot{h'} \Delta \theta, \]
where \( h' = \left( \frac{dh}{d\theta} \right)_{\theta=\theta_0} \). Substituting for \( \Delta \dot{\omega} \) twice, it follows from (14) that
\[ \Delta \ddot{\theta} + c_2 \Delta \dot{\theta} + c_1 \Delta \theta + c_0 \Delta \theta = 0, \]  
where the constant coefficients are given by
\[ c_2 = \frac{b}{m}, \]  
\[ c_1 = \omega_0^2 \sin^2(\theta_0) - \frac{\Gamma d}{l} h'_0 \cos(\theta_0), \]  
\[ c_0 = -2\Gamma \sin(\theta_0) \cos(\theta_0) h' \omega_0. \]

Equation (16) takes the same form as the linearized equations of the centrifugal steam engine governor.

Maxwell showed that the solutions of (16) are stable if the coefficients satisfy the inequalities
\[ c_0 > 0, \]  
\[ c_1 > 0, \]  
\[ c_2 > 0, \]  
\[ c_1 c_2 > c_0. \]  

To satisfy (20)–(22) we require friction to be present \((b > 0)\) and the first derivative of \( h(\theta) \) to be negative \((h'_0 < 0)\); both of these requirements obtain naturally. Inequality (23) is not at all transparent until we follow Vyshnegradskii, who, for the centrifugal steam engine governor, defined the nonuniformity of performance \( v \). The analogous parameter here is
\[ v = \left| \frac{d \omega_0}{dh_0} \right| = \left| \frac{d \omega_0}{dh_0} \frac{d \theta_0}{dh_0} \right| = \frac{1}{2} \sqrt{\frac{8}{l} \frac{1}{h'_0} \sin^2(\theta_0)} \]  

Vyshnegradskii’s nonuniformity of performance describes how steam engine angular speed changes with load. In our case (24) describes how auxiliary shaft equilibrium angular speed changes with equilibrium flyball height. In terms of \( v \), (23) can be rewritten as
\[ A(s-1) + \frac{d}{2l} b > 0, \]  
where \( s = bv/m \Gamma \) and \( A = \omega_0 \sin(\theta_0) = \sqrt{\omega_0^2 - (g/l)\omega_0^2} \). Note that \( s \) is exactly analogous to the stability factor obtained by Vyshnegradskii for the centrifugal governor. That is, if in (10) we replace \( \Gamma \) by the appropriate steam engine parameter, we obtain the same stability factor as obtained by Vyshnegradskii. In that case, he found that stability of the centrifugal governor system requires \( s - 1 > 0 \); here we see that stability for the tangential governor can occur for smaller values of \( s \). Unlike the centrifugal governor case we find that, for a given stability factor, system stability depends on the equilibrium angular speed. In deriving the stability criterion we assume that the auxiliary shaft equilibrium angular speed exceeds \( \sqrt{g/l} \); as noted above, for lower angular speeds the equilibrium angle is \( \theta_0 = 0 \) independent of the auxiliary shaft angular speed, which is useless for a regulator.

To directly compare the stability criteria for the tangential and centrifugal governors in the context of the Brennan torpedo, we must ensure that both governors are the same size so that they can fit into the same confined space. To meet this constraint, we assume that the governor must fit inside a cylinder of radius \( r \). For the centrifugal governor, therefore, we have the maximum dimensions \( l \) and \( d_{\text{cent}} \) constrained by \( r = l + d_{\text{cent}} \). For the tangential governor, however, the constraint equation is different, as becomes clear from Figure 5(a), namely, \( r = \sqrt{l^2 + d_{\text{tang}}^2} \). Thus, to compare the two types of governors, assuming the same swinging arm length \( l \), we assume that the horizontal arm lengths satisfy
\[ d_{\text{cent}} = \sqrt{l^2 + d_{\text{tang}}^2} - l. \]  
To summarize, we have shown that the tangential governor can work in a stable manner; the stability criteria are somewhat relaxed compared with the centrifugal governor, although auxiliary shaft angular speeds must
exceed a minimum value. To compare the two types of governors in the context of the Brennan torpedo, we must restrict dimensions so that both can move freely within the limited space available.

SIMULATING THE TANGENTIAL GOVERNOR
To describe the effect of the tangential governor, we numerically integrate the equations of motion (8) and (10). It is convenient to introduce the dimensionless parameters

\[
\tau = \sqrt{\frac{g}{l}}, \quad W = \sqrt{\frac{l}{g}} \dot{\omega}, \quad B = \sqrt{\frac{l}{g}} \frac{b}{m}, \quad G = \sqrt{\frac{m}{g}} \frac{G}{l}, \quad D = \frac{d}{l} \quad (27)
\]

where \(d\) is assigned the value of either \(d_{\text{tang}}\) or \(d_{\text{cent}}\). For the parameter values \((D, B, G) = (1, 0.5, 1)\) we obtain from (25) the stability curve plotted in Figure 5(b); this curve is the left side of (25). The stability curve for the centrifugal governor is also plotted, accounting for the constraint (26). Both systems are predicted to be stable if their stability curves exceed zero and thus, from Figure 5(b), we predict that the tangential and centrifugal governors are both unstable for dimensionless angular speeds below 1.4, that the centrifugal governor is slightly more stable for intermediate angular speeds between 1.4 and 1.8 and that the tangential governor is more stable for high angular speeds above 1.8. Simulation follows these predictions. If the parameter values \((D, B, G)\) are altered, then the stability curves change; numerical simulations remain in agreement with predictions.

To provide a specific example, consider Figure 6. Here we numerically integrate the equations of motion for the parameter values used in Figure 5, with the shaft dimensionless angular speed 2.5. From Figure 5 we expect the tangential governor to be more stable than the centrifugal governor, and it is clear that this is the case. For the lower shaft angular speed \(W = 1.5\), the stability curves of Figure 5(b) predict that the centrifugal governor is slightly more stable, and further numerical integration confirms this prediction.

CONCLUSIONS
We have found that the tangential governor is more stable than the centrifugal governor of comparable size or can be made more stable by choosing a high auxiliary shaft angular speed. This result is to be expected, given that the tangential governor is sensitive to both angular speed and angular acceleration of the auxiliary shaft, whereas the centrifugal governor is sensitive only to auxiliary shaft angular speed. From (7) it follows that the degree of sensitivity of the tangential governor to acceleration depends on the geometry, namely, sensitivity increases as the length of the horizontal arm increases relative to the length of the swinging arms. This fact was known to the designers of the Brennan torpedo in the late 19th century. We believe that these designers decided on a tangential governor to control
the depth of their torpedo because, given a high auxiliary shaft angular speed and the spatial confinement, this type of governor is more stable than its better-known cousin. The tangential governor is also a neater solution than the multiple-component diaphragm-and-pendulum method, assuming the availability of an auxiliary shaft whose angular speed changes with depth.

One possible objection to the idea of a flyball governor solution to the torpedo depth-control problem, or rather to the above analysis of it, is that we have not considered the equations of motion for the pitch of the torpedo. That is, we have assumed that the auxiliary shaft of Figure 3 is vertical. In fact, from the data we have about torpedo “porpoising,” it is not difficult to show that the maximum deviation of this axle from the vertical direction when placed inside a porpoising torpedo, is about 3°, and this angle changes slowly compared with the timescale of the feedback mechanism. Thus we can expect that the influence of torpedo pitch angle and its rate of change of this angle is small.

Other possible flyball governor designs might be considered for regulating torpedo depth. For example, what about a hybrid governor with a ball-and-socket joint connecting horizontal and swinging arms, that is, at locations D and E of Figure 2? Such a free-swinging arrangement might be expected to display the properties of both the centrifugal governor and the tangential governor, but in fact it does not. For the hybrid governor the centrifugal force dominates, and the angular-speed-dependent tangential equilibrium positions of Figure 4 disappear. The only tangential equilibrium angle is at \( \theta = 0^\circ \). Perhaps this dominance of centrifugal force points to a difficulty of implementation for a tangential governor. The design shown in Figure 3 is subject to stress, due to centrifugal forces, at the joints where the horizontal and swinging arms are connected; the flyballs want to swing outward but are not able to do so. Perhaps careful design of these joints was needed to ensure that, for example, the friction coefficient is not sensitive to flyball speed. Whether this is the case or not, it is clear that a tangential governor requires better engineering than does a centrifugal governor, and this fact alone explains why we hear little of the tangential governor. Before gyros took over from centrifugal governors, there was a transition period of a decade or so during which engineers searched for more capable regulators than currently existed, to satisfy the more demanding requirements of new technology.

**REFERENCES**


**AUTHOR INFORMATION**

**Mark Denny**

Mark Denny earned a Ph.D. in theoretical physics from Edinburgh University, Scotland, and then pursued research at Oxford University from 1981 to 1984. He was subsequently employed by industry, where he worked as a radar systems engineer. He has written 50 papers on radar signal processing and physics, plus five popular science books. He is semiretired and lives on Vancouver Island.

**Gabe Graham**

Gabe Graham received the M.S. in mechanical engineering from the University of California in San Diego in 2007. His thesis project was the design, fabrication, and control of a one-legged balancing robot. He was subsequently employed by Rasirc, a startup company developing steam-purification systems for the semiconductor industry. He is currently employed by General Atomics Aeronautical, developing laser and camera systems for airborne applications.

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**ASK THE EXPERTS**

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