FEATURE

The Outrigger

A prehistoric feedback mechanism

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Standing on the beach at Waikiki, looking at an outrigger canoe, my then 3-year-old son DJ asked, "How does that work?" He was pointing at the outrigger (Figure 1). Like any dutiful father and engineer, I started trying to explain the use of the outrigger. Halfway through my explanation, I realized that I was describing a feedback mechanism. A cursory knowledge of Polynesian history suggested that this ancient device was quite possibly the first feedback mechanism created by humanity. This article is my attempt to chronicle the history of this remarkable bit of Stone Age control engineering, which predates the float valve by at least a millennium.

There are two classes of floating watercraft: those that owe their buoyancy to their materials, and thus can float irrespective of shape, and those that owe their buoyancy to their shape and the amount of water they displace. While the reed boats of ancient Egypt and the balsa rafts of Peru are in the former class [1], the dugout canoe prevalent in Polynesia belongs to the latter class [2]. Although the dugout is made from lighter-than-water materials that are buoyant on their own, the hollowed-out, semicylindrical shape allows it to achieve greater buoyancy by displacing considerably more water. However, due to its semicylindrical shape, the dugout canoe suffers from an increased tendency to capsize compared to plank-built vessels (vessels built of planks attached to a frame). Unlike the plank-built vessels, there is limited ability to increase a dugout's resistance to capsizing (that is, increase its roll stability) by widening or changing the shape of the hull. Thus, the dugout canoe begs for a different solution to the roll stability problem.

At its most basic level, an outrigger consists of a float

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attached by means of one or more booms to the gunwales (top edge) of a boat. While modern outriggers can be made from a variety of sturdy, buoyant materials, the outrigger float has traditionally been constructed from a piece of light wood. It is most often associated with the dugout canoe. Outriggers can also be found on plank-built boats, although the necessity is lower for these vessels since builders of plank boats have more ability than the makers of dugout canoes to improve the roll stability by changing the hull shape. The action of an outrigger is twofold. First, the outrigger adds buoyancy to the vessel since outriggers are made of materials that float irrespective of their shapes. More importantly, the addition of a float at the end of a boom dramatically increases the roll stability of small canoes.

Figure 1. *Outrigger canoes. The outrigger is an add-on mechanism that augments roll stability in a narrow-hulled boat such as a dugout. The operation of the outrigger is rather simple. When the canoe rotates so as to raise the boom from the water, the outrigger's weight at the end of a moment arm provides torque to rotate the boom back to the surface. When the rotation of the canoe pushes the boom into the water, the buoyancy of the boom restores the boom to the surface of the water.*

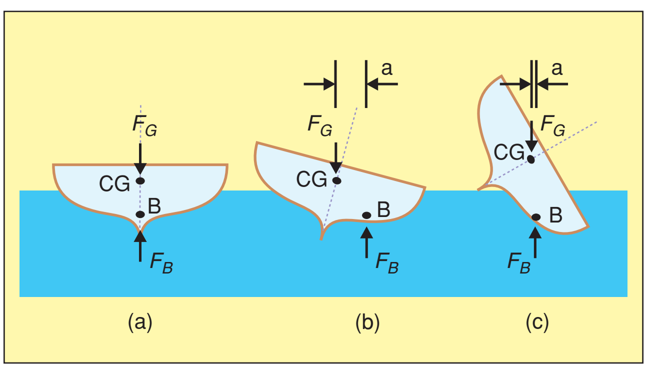

Figure 2. *Righting moment for a typical plank boat hull on a horizontal water surface (based on [24, p. 252]). (a) With no tilt, the center of gravity and the center of buoyancy are aligned vertically. As the boat tips, the center of buoyancy translates horizontally relative to the center of gravity by a distance a. (b) These two opposing forces, acting through a moment arm of length a, generate a righting moment. (c) As the boat tips further, the righting moment decreases as the center of gravity moves above the center of buoyancy.*

Until the publication of Otto Mayr's *The Origins of Feedback Control* [3], [4], the consensus among control engineers was that the original feedback mechanism built by humans was the flyball governor [5]. However, Mayr's work established convincing evidence that the water clock of Ktesibios, who lived in Alexandria in the first half of the third century BC, was the first recorded feedback mechanism [3]. This innovation predates the flyball governor by two millennia. A series of devices based on the float valve followed in the succeeding centuries, with most appearing in the Middle East.

Otto Mayr's book also established a set of criteria for determining whether a device is in fact a feedback mechanism:

> The three criteria we have now obtained contain a sufficiently complete definition of the concept. Briefly repeated, they are:
> 1) The purpose of a feedback control system is to carry out commands; the system maintains the controlled variable equal to the command signal in spite of external disturbances.
> 2) The system operates as a closed loop with negative feedback.
> 3) The system includes a sensing element and a comparator, at least one of which can be distinguished as a physically separate element. [3]

Using these criteria, we show that the outrigger on an outrigger canoe, the device that Thor Heyerdahl referred to as "the most desirable of the Asiatic navigational inventions" [1, pp. 160–161], is in fact a feedback mechanism. Furthermore, we show that the outrigger predates the float valve by at least 1,000 years, thus making the outrigger the earliest documented feedback mechanism built by humans.

Basic Roll Stability Analysis

A key feature of any watercraft is its roll stability. Simply put, a watercraft with poor roll stability capsizes easily. A craft made of heavier-than-water materials relies on the displacement of water to achieve buoyancy. In such situations, capsizing leads to the waterlogging of the vessel, which then sinks. However, even watercraft made of buoyant materials can capsize.

Resistance to capsizing, or roll stability, comes from having a righting moment that resists roll moment disturbances. Consider the typical plank-built boat cross section in Figure 2. The boat floats because it displaces water equivalent to its weight. Just as the center of gravity is the point at which the force of gravity can be considered to be acting, the center of buoyancy is the point at which the buoyant forces can be considered to be acting. For most boats with bilateral symmetry about the center line, the center of gravity is above the center of buoyancy [Figure 2(a)]. When the boat rolls around its center of gravity [Figure 2(b)], the center of buoyancy translates horizontally relative to the center of gravity by a distance a, resulting in a moment with magnitude $[F_G + F_B]a$ opposing the rotation. As the center of buoyancy moves away from the center of gravity, the righting moment increases. After the righting moment reaches a maximum, the moment arm and the righting moment begin to decrease [Figure 2(c)]. As the roll angle increases, the center of buoyancy moves closer to the center of gravity, lowering the effective righting moment. A typical shape of a righting moment curve is shown conceptually in Figure 3.

The shape of the hull has a dramatic effect on the shape of the righting moment curve. In particular, a perfectly cylindrical hull with a circular cross section, as shown in Figure 4(a), has no righting moment since for any angular displacement the center of buoyancy remains below the center of gravity, making the moment arm $a = 0$ [Figure 4(b)]. Adding ballast at the bottom of the hull lowers the center of gravity [Figure 4(c)] and allows for a righting moment [Figure 4(d)]. A hull made from a section of a cylinder [Figure 4(e)] has a small inherent righting moment since the center of gravity is lower than its original location in the cylindrical hull, while the center of buoyancy is unchanged.

One possibility for adding a righting moment to a cylindrical hull is to attach the hull to a second cylindrical hull or a simple float. The farther apart the two hulls, the easier it is to generate a righting moment, at least for small angles. This modification can be realized in a number of ways. Here we concentrate on three methods closely associated with outrigger technology: a single outrigger, a double outrigger, and a double-hull canoe, shown in Figure 5. These designs are based on similar principles. All three methods are present in the sailing technology of the Austronesian peoples. (The term Austronesian is used by Doran [6] and others to describe the people that migrated from Asia to Australia and into the Pacific. The name denotes a superset of the indigenous peoples of Australia, Indonesia, Malaysia, and Polynesia.) The tradeoffs in choosing one type of watercraft over another seem to have been centered around ease of manufacture, structural safety, and crew requirements for each type of craft.

Qualitatively, the operation of the outrigger is simple. When the canoe rolls so as to raise the float from the water, the weight of the float at the end of a moment arm provides a moment that rotates the float back to the surface. When the rotation of the canoe acts to push the float into the water, the buoyancy of the float acts to restore the float to the surface of the water. In other words, the outrigger senses and resists angular disturbances, making it a true negative feedback mechanism.

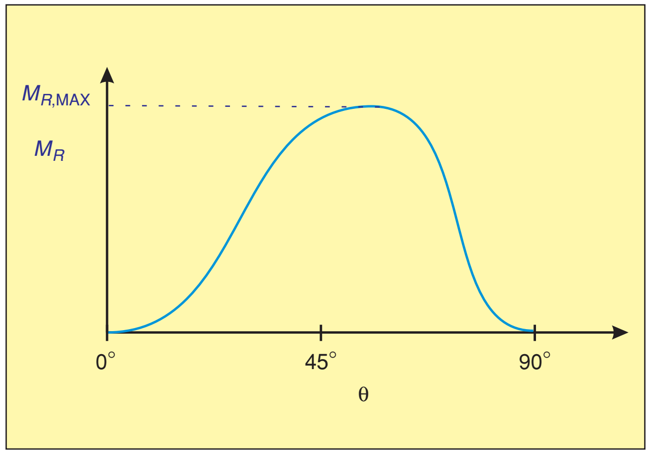

Figure 3. *A typical righting moment curve for a boat hull such as the one shown in Figure 2. The righting moment M_R increases with increasing roll angle θ until M_R reaches its maximum value $M_{R,\text{MAX}}$. The shape of the righting moment curve depends on the shape of the hull.*

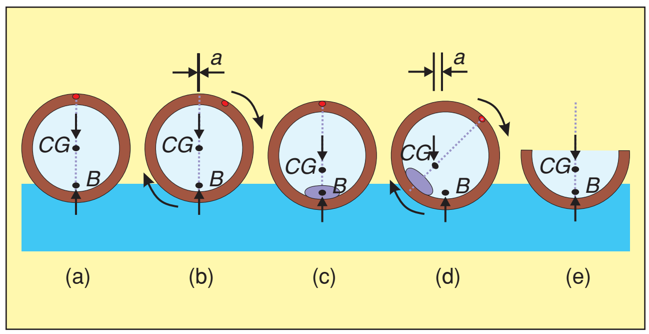

Figure 4. *Roll stability and cylindrical hulls. A cylindrical hull lacks roll stability because the center of buoyancy remains below the center of gravity. Thus, even though the hull in (b) is rotated from that in (a), there is no righting moment. Adding ballast at the bottom (c) adds stability, since a rotation (d) causes the center of buoyancy and the center of rotation to translate horizontally relative to each other by a distance equal to the moment arm a. The buoyant force and the force of gravity then provide a righting moment. Dugout canoes are carved out of roughly cylindrical tree trunks and so retain the shape of a section of a cylinder. An unballasted dugout hull (e) made from a section of a cylinder has poor roll stability.*

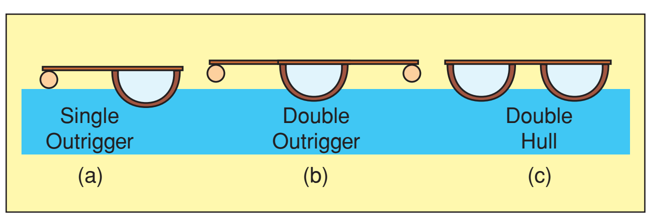

Figure 5. *Adding outrigging to stabilize a dugout hull. The three styles of outrigger technology include (a) the single outrigger, (b) the double outrigger, and (c) the double hull.*

Since the righting moment applied by the outrigger returns the canoe to a level position more quickly than without the outrigger, the outrigger can be viewed primarily as a stabilization device. However, the outrigger also enhances the disturbance rejection ability of the dugout canoe. In particular, the outrigger allows the boat to reject both internal disturbances (someone moving in the boat) and external disturbances (the force of waves and wind on the boat).

The Outrigger as a Feedback Mechanism

The outrigger may have evolved from the custom of lashing two canoes together to provide greater roll stability. At first look, however, the double-hulled canoe does not seem to qualify as a feedback mechanism since the second hull increases the cargo capacity of the ship and thus does more than provide roll stability. Unlike the outrigger, it is hard to distinguish which hull is the feedback mechanism and which hull is the main part of the boat. The outrigger, on the other hand, does not provide extra cargo capacity and its sole purpose is to augment roll stability.

From the perspective of Mayr, the outrigger satisfies all three criteria for a feedback mechanism [3]:

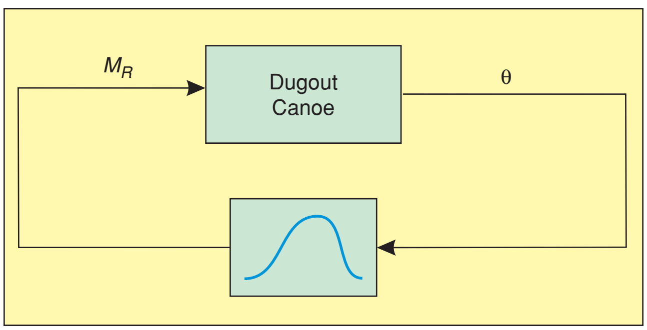

Figure 6. *Roll stability of a single-hull canoe as a feedback loop. The righting moment M_R is due to a shift in the center of buoyancy relative to the center of gravity, which, in turn, is a function of the roll angle θ.*

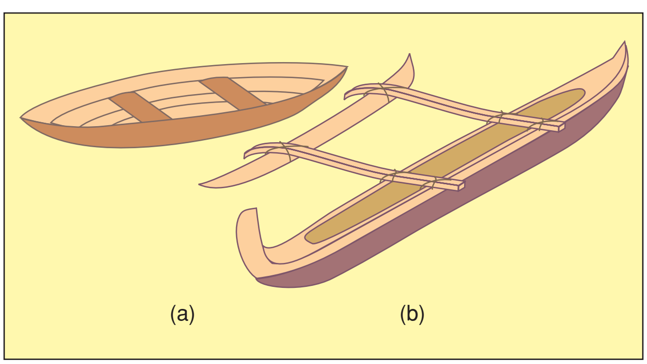

Figure 7. *Comparison of (a) a plank-built vessel with (b) an outrigger canoe. The main hull of the outrigger canoe is much narrower than the plank-built hull, resulting in a smaller righting moment. This difference is the main reason for adding the outrigger.*

1) *The outrigger enhances the roll stability of the canoe.* The outrigger helps prevent the canoe from capsizing. In this respect, the regulated variable is the angle between the bottom of the canoe and the water surface. The outrigger performs this function in the presence of disturbances that are internal (movement within the boat) or external (waves and wind).
2) *The outrigger provides negative feedback.* From a nominal position on the water, the buoyancy of the outrigger resists rotations that tend to submerge it, while the weight of the outrigger resists rotations that tend to raise it out of the water.
3) *The outrigger is a separate element from the canoe.* The outrigger is the sensor, feedback algorithm, and actuator for detecting and correcting rotations. Its only purpose is to enhance roll stability and disturbance rejection.

In many respects, the behavior of the outrigger float is similar to the behavior of a float valve. Like the float valve, the outrigger float provides both the sensing and the actuation. As we shall see later, the sensing and actuation act in a closed loop. Finally, within this closed-loop system is a control algorithm, and we can derive an error equation associated with this algorithm.

The double outrigger makes the stabilization problem symmetric by placing a buoyant float on both sides of the main hull. The double-hulled canoe is also a symmetric design. Based on a strict interpretation of the Otto Mayr criteria, the second hull might not be considered a feedback mechanism. However, the double-hull canoe is an obvious member of the outrigger family, springing from the same culture and used in parallel with the outrigger canoe. Viewed in the context of other outriggers, the double hull should be seen as a stabilization device, where each hull helps stabilize the roll of the other hull. (See "Double Hull Versus Outrigger" for more discussion on this.) Thus, we consider all three boat designs to be variations of outrigger technology. As such, the age of one over another is not critical for understanding the age of outrigger technology.

Simple Analysis of the Outrigger Loop

To analyze the feedback effect of the outrigger, first consider the block diagram of a single-hulled boat without an outrigger, as shown in Figure 6. While this block diagram simply shows the boat dynamics, these dynamics are stable due to the righting moment (actuation) provided by the translation of the center of buoyancy relative to the center of gravity. The righting moment provides sensing, negative feedback, and actuation. Thus, these boat dynamics form a feedback loop. However, this feedback loop is not the result of an external device. Using the Mayr criteria, this built-in feedback is not a feedback mechanism.

Plank-built boats [Figure 7(a)] offer the builder considerable design freedom to change the shape of the hull. In contrast, a dugout canoe is hollowed out of a single tree trunk [Figure 7(b)]. This restriction to a single tree trunk limits the shape of the hull to one that closely follows a portion of a cylinder. Just as a cylinder has no righting moment (Figure 4), a section of a cylinder has a small inherent righting moment, as shown in Figure 4(e). In other words, the roll stability is poor. However, the addition of an outrigger [Figure 8(a)] increases the righting moment considerably.

In Figure 9, the effect of the outrigger is modeled as a secondary loop around the original righting moment loop of Figure 6. From this perspective, the canoe dynamics form an inner-loop feedback system, with the outrigger generating the outer loop. This outer loop transforms a craft that is safe only on flat water into one that is seaworthy.

In contrast to the inner loop of the main hull, the outrigger is an add-on mechanism. Thus, the increased stability and disturbance rejection provided through feedback by the outrigger's outer loop qualifies the outrigger as a feedback mechanism by the Mayr criteria. The outer loop becomes necessary only when the inner loop cannot provide sufficient righting moment to render the boat seaworthy. Cultures that had plank-built boats did not have a need for this outer loop. Only cultures that sought to explore the oceans with dugout hulls found outrigger technology necessary.

A change in the roll angle θ corresponds to a change in the height of the outrigger float. When the float is in contact with the water, this change in height is a change in depth. However, whether in air or in water, the change in float height or depth results in a force opposing that change.

Double Hull Versus Outrigger

The choice of using a double-hulled canoe versus a single-hulled canoe with an outrigger can be seen as an issue of ease of manufacture, human interface, capacity, and speed. Traditionally, one of the most difficult tasks was finding two matching logs of sufficient size to make a large double-hulled voyaging canoe. Among the most prized logs for canoe building were Oregon pines that fell into the ocean and drifted to Hawaii. These logs were so valued that one log would be kept for years until a matching one drifted ashore [2], [8]. Double-hull canoes were typically large devices, requiring several men for proper handling; they were not appropriate for individual use. Outrigger canoes have no such manufacturing issues since the outrigger does not have to match the main hull. Outriggers were generally small enough for a single person to handle, although larger versions were used for long voyages.

Furthermore, it should be noted that the materials used to strap together the two hulls of a double canoe limited the distance between the hulls. Thus, these canoes had a much narrower aspect ratio than their descendants, the modern catamaran and trimaran. Finally, there is the issue of speed. The Polynesians have long been aware of the faster speed of an outrigger compared to a double-hull canoe of similar size. This advantage is clear from the folklore documented by Peter Buck [7, p. 38]:

> Though double canoes held more men, provisions, and water, it is evident from traditional stories that outrigger canoes were also used on long voyages. The *Hohio* on which Hiro made his last voyage is described as having a float (*ama*) of *tamanu* wood soaked in sea water to destroy borers, and then scraped with coral rubbers. The outrigger canoe, by affording less friction in the water, was faster; and with the wind on the outrigger side, the canoe was allowed to keel over so that she sailed with the outrigger float out of the water. Men watched with alert eyes, and if the float rose too high, they clambered out on the outrigger booms to press the float down and so prevent capsizing.

More instructive is the following story relayed by Buck [7, pp. 38–39]:

> When Nuku sailed from Tahiti to New Zealand to fight Manaia, he had two double canoes and one outrigger canoe. After a voyage of over 2000 miles upon an affair of honour, he finally sighted Manaia's double canoe sailing along the coast, and he gave pursuit. The outrigger canoe, acting as a fast cruiser, came up on the seaward side and forced Manaia's canoe toward the shore while the double canoes, like battleships, lumbered up behind. Finally Manaia was forced ashore, and the battle was waged on land. After a desperate battle, peace was made between the two valiant warriors. Nuku decided to return to Tahiti, but, as the season was late, he converted his double canoes into outrigger canoes in order to make a speedier voyage.

Thus, we see that the ancient Polynesians used the outrigger and double hull interchangeably, reinforcing the idea that these devices are simply two embodiments of the same technology.

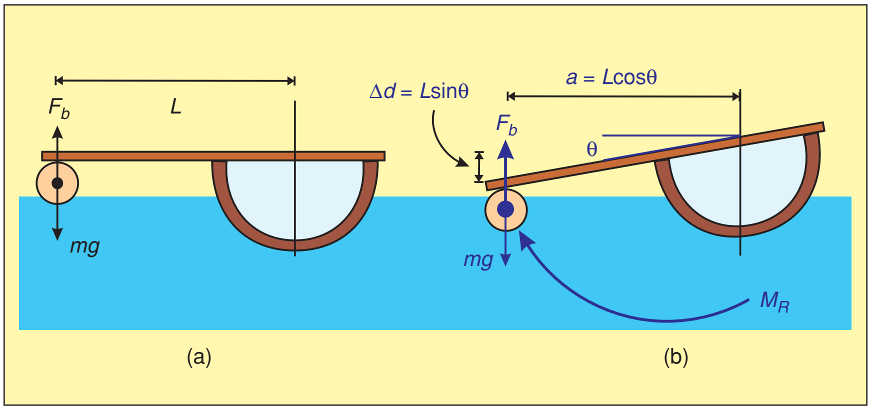

Figure 8. *Adding an outrigger to a semicylindrical hull. The outrigger (a) produces a righting moment that improves roll stability. (b) A rotation of the hull through an angle θ results in a change $\Delta d = L\sin\theta$ in float depth. The righting moment M_R is due to the resultant of the buoyant force F_b and the weight of the float mg acting through the moment arm $a = L\cos\theta$.*

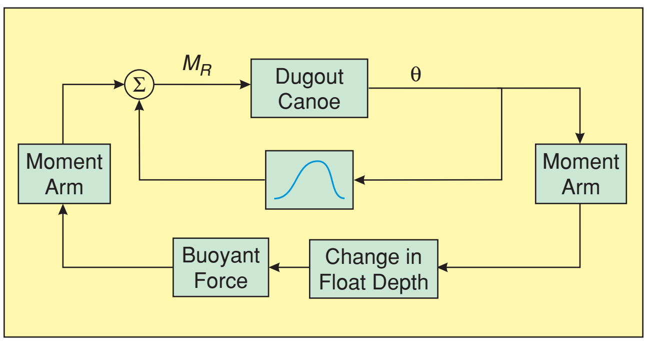

Figure 9. *In an outrigger canoe, the inner loop from the single hull is augmented by an outer loop that dramatically increases the righting moment and improves disturbance rejection. In this drawing, M_R is the righting moment and θ is the angle between the center of the bottom of the hull and the water. The righting moment opposes a nonzero θ.*

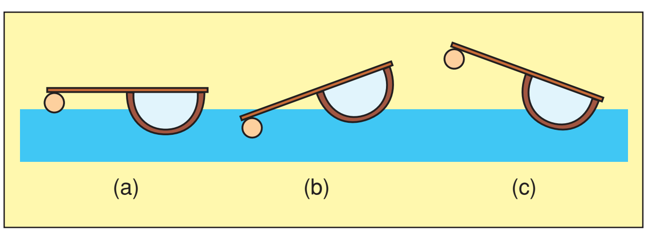

Figure 10. *The different operating modes for a single-outrigger canoe. (a) For small roll angles, a linearized error equation governs the moments that arise when the float is disturbed from its normal buoyant position. In (b) the float is fully submerged. While the buoyant forces are largest here, this configuration is a dangerous operating point (see "Sailing into the Wind—Shunting Versus Tacking"). In (c), the float is fully out of the water. This situation occurs when the outrigger is on the windward side, the side from which the wind is coming. In this mode, sailors climb out onto the outrigger to increase the righting moment.*

This force acting on the moment arm of the boom results in a righting moment that drives θ back to zero.

The outrigger canoe operates in three modes, as shown in Figure 10. For small deviations of the float from the nominal buoyant position [Figure 10(a)], one can derive a simple error equation. For the configuration in Figure 10(b) in which the float is fully submerged, the buoyant force is maximized. The configuration in Figure 10(c), where the float is fully out of the water, is common when the wind blows perpendicular to the sail, with the outrigger on the windward side of the boat. In this case, sailors climb out onto the outrigger to increase the righting moment, equivalent to "hiking out" on a modern sail boat.

Focusing on the nominal configuration in Figure 10(a), the angle θ of the center of the main hull with the water surface results in a change Δd in float depth. The change in buoyant force due to the change in depth $F_B(d+\Delta d) - F_B(d)$ acts in the opposite direction of Δd. This change in buoyant force acts on the moment arm a to create a righting moment that drives θ to zero. This righting moment augments any righting moment generated by the main hull. For small deviations about the nominal float depth, we can compute the magnitude of the righting moment by computing the buoyant force for a given float cross section. For each cross section, an equation can be generated in terms of the nominal depth d of the float, the change Δd in depth, and the float geometry. For the results given below, l is the length of the float, w is the width, ρ is the density of the displaced water, and g is the acceleration due to gravity. For details of the derivation, see "Calculation of Buoyant Forces for Various Float Shapes."

Referring to Figure 8(a), the float has a nominal depth of d at which the buoyant force $F_B(d)$ exactly cancels the force of gravity, that is, $F_B(d) = mg$. For a disturbance that perturbs the depth away from the nominal by Δd, the resulting moment is given by

$$\begin{aligned} M_R(\Delta d) &= [F_B(d+\Delta d) - mg]\,a \\ &= [F_B(d+\Delta d) - F_B(d)]\,a. \end{aligned} \quad (1)$$

Computing the righting moment for different configurations essentially consists of computing $F_B(d+\Delta d) - F_B(d)$. For a rotation of the main hull through an angle θ as shown in Figure 8(b), the change in depth Δd is given by

$$\Delta d = L\sin\theta, \quad (2)$$

while the moment arm a of the buoyant force is given by

$$a = L\cos\theta. \quad (3)$$

For small θ, (2) and (3) become

$$\Delta d = L\theta, \quad a = L. \quad (4)$$

We see that the length of the outrigger boom makes the moment arm a in Figure 8 considerably larger than for the cylindrical and semicylindrical hulls of Figure 4. The righting moment M_R is given by

$$\begin{aligned} M_R(\Delta d) &= [F_B(d + L\sin\theta) - mg]\, L\cos\theta, \\ &\approx [F_B(d + L\theta) - F_B(d)]\, L. \end{aligned} \quad (5)$$

The additional righting moment $M_R(\Delta d)$ generated by the outrigger regulates the angle of the main hull with respect to the water surface. We can follow this analysis further to calculate the change in buoyant force with respect to change in depth $F_B(d + \Delta d) - F_B(d)$ for different outrigger float shapes. However, these results affect only the magnitude and linearity of the buoyant force with respect to Δd, not its direction. In a static analysis, the outrigger always increases the righting moment, making the canoe more stable and able to reject larger disturbances.

Buoyant Forces for Different Outrigger Shapes

We first consider the rectangular float shown in Figure 11(a). This float is the simplest to consider since it yields a linear error equation. Specifically, the resultant buoyant force as a result of the change in depth Δd is

$$F_{B,\Delta_d} = \rho g \Delta d l w. \quad (6)$$

Here l is the length of the float, w is the width, ρ is the density of the displaced water, and g is the acceleration due to gravity.

For the rectangular float shape, the buoyant force $F_{B,\Delta d}$ is independent of the nominal depth d and linear in Δd. A linear error equation is convenient, but more likely float shapes are the triangular or circular cross sections shown in Figure 11(b) and (c), respectively. The circular cross section corresponds to the shape of a tree limb, commonly used for traditional outriggers. The triangular cross section is common for modern, V-shaped hulls.

For the cross section in the shape of an isosceles triangle, we would like to calculate the buoyancy as a function of the depth d of the section. In this case, the difference in forces is given by

$$\begin{aligned} &F_B(d + \Delta d) - F_B(d) \\ &\quad = [V_{imm}(d + \Delta d) - V_{imm}(d)]\,\rho g \\ &\quad = l\,[A_{d+\Delta d} - A_d]\,\rho g \\ &\quad = l\left(2d\Delta d + (\Delta d)^2\right)\tan\frac{\phi}{2}\rho g, \end{aligned} \quad (7)$$

where ϕ is the angle of the triangle corner in the water. Now, the feedback term depends on the nominal depth d and has a quadratic component.

By repeating these calculations for the circular cross-sectional float with radius r, the difference in forces is equal to

$$\begin{aligned} &F_B(r, d + \Delta d) - F_B(r, d) \\ &\quad = l\Bigg[\Bigg(r^2 \mathrm{Cos}^{-1}\frac{r - (d + \Delta d)}{r} \\ &\qquad - (r - (d + \Delta d))\sqrt{2r(d + \Delta d) - (d + \Delta d)^2}\Bigg) \\ &\qquad - \left(r^2 \mathrm{Cos}^{-1}\frac{r - d}{r} - (r - d)\sqrt{2rd - d^2}\right)\Bigg]\rho g. \end{aligned} \quad (8)$$

For small Δd, (7) and (8) become linear in Δd, which matches physical intuition.

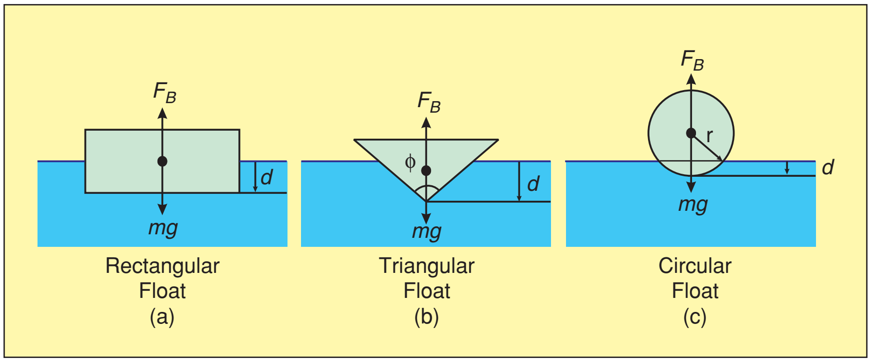

Figure 11. *Different float shapes, which yield different error equations. (a) Although it is an uncommon outrigger shape, the rectangular float gives a buoyant force that is linear with the change in the nominal depth d. The rectangular shape gives the simplest error equation. The other shapes give more complicated equations that can be linearized for small changes in the nominal depth. (b) The triangular shape is a modern innovation, corresponding to V-shaped hulls. (c) A circular shape is typically made from a tree limb.*

The Origins and History of Outrigger Canoes

Debates about the origins of outrigger technology are intimately connected to debates about when the South Seas were initially populated and by whom. Central to these debates are questions about the seaworthiness of Polynesian canoes and the skills of Polynesian sailors. The ancient Polynesians had no written language. Furthermore, there are no traces of the ancient canoes, which were made of soft woods that swiftly decomposed in the warm waters of the South Pacific and Indi-

Calculation of Buoyant Forces for Various Float Shapes

We control engineers love error equations, particularly when the equations are linear. A means for determining the difference between the desired value and the current value is at the heart of feedback. Thus, an error equation is crucial for a system operating in closed loop.

Of the three configurations mentioned in the main text, namely, the float completely out of the water, the float completely submerged, and the float in a neighborhood of its nominal depth, the first two can be analyzed easily. Gravity acts on a float completely out of the water to push the float back toward the surface. Likewise, buoyancy is largest when the float is fully submerged. In this case, the static buoyant effect may be counteracted or enhanced by the behavior of the float under the surface, where the float may behave like a diving plane on a submarine when the boat is moving. The desire to avoid this situation is one of the main justifications for the shunting method of sailing into the wind. (See "Sailing into the Wind—Shunting Versus Tacking.")

However, the last situation, where the float is at a small deviation about its nominal depth, allows us to calculate an error equation for each of three different simple cross sections. All we are doing here is adding equations to the obvious: when something buoyant is displaced from its nominal depth, the actions of buoyancy and gravity act to restore it to that nominal depth. Any cross-sectional shape of a float will accomplish this, although the actual restoring force will differ with the shape.

The first cross-sectional shape for a float is a rectangle, as seen in Figure 11(a). This shape is the simplest to compute and gives a linear error equation. We start by summing forces in the vertical direction ΣF_y to obtain

$$\Sigma F_y = F_B - W = 0, \tag{9}$$

where F_B is the buoyant force on the float and W is the weight of the float. For any float with a constant cross section and area A_b, the weight mg of the float equals the weight of the displaced water

$$F_B = mg = V_{imm}\rho g, \tag{10}$$

where V_{imm} is the volume of the immersed portion of the float, that is,

$$V_{imm} = A_b d. \tag{11}$$

Here, A_b is the area of the float bottom (width × length), d is the depth of immersion, ρ is the density of water, and g is the acceleration due to gravity.

Now, assuming that the depth of the float is disturbed away from the nominal d by Δd, it follows that

$$\begin{aligned}\Sigma F_y &= F_B - W \triangleq F_{\Delta d}\\ &= \rho g(d + \Delta d)A_b - mg\\ &= \rho g d A_b - mg + \rho g \Delta d A_b.\end{aligned} \tag{12}$$

In equilibrium, the force of gravity is exactly canceled by the buoyant force

$$mg = \rho g d A_b, \tag{13}$$

and thus (12) reduces to the resultant buoyant force $F_{B\Delta d}$ as a result of the change in vertical displacement, where $F_{B\Delta d}$ is given by

$$F_{B\Delta d} = \rho g \Delta d A_b, = \rho g \Delta d l w. \tag{14}$$

Here, l is the float length and w is the float cross sectional width. Since Δd is defined as positive in a downward direction and $F_{\Delta d}$ is positive in an upward direction, we have confirmed what we already knew: the float resists any change away from equilibrium.

A rectangular float cross section is convenient for calculation since it leads to a linear error equation (14). However, from the perspective of boat building, the rectangular shape is less likely than a triangular cross section or a circular cross section seen in Figure 11(b) and (c), respectively. Very simply, trees are not rectangular and traditional canoes are built from tree limbs. The Polynesians had stone tools, but no metal for saws. Thus, the most likely an Oceans. The absence of written records and material remains of the canoes has fueled the ongoing debates.

The traditional view of Polynesian migration as island hopping across the Pacific in deliberate exploration was codified by Peter Buck in his classic book *Vikings of Sunrise*, later reissued as *Vikings of the Pacific* [7]. This theory came under attack from two sources, Thor Heyerdahl and Andrew Sharp. Heyerdahl claimed that the Polynesian canoes were too primitive to sail against the prevailing current and wind, which blows from east to west

float cross-sectional shape in a traditional canoe is circular. However, a V-shaped hull is quite common in ship building today and one might encounter a triangular float shape in modern designs.

For a cross section in the shape of an isosceles triangle, we would calculate the buoyancy as a function of the depth of the section d. Applying (10) yields

$$V_{imm} = A_d l, \tag{15}$$

where l is the length of the float into the page and A_d is the area of the submerged triangular cross section as a function of d given by

$$A_d = \frac{1}{2} bd, \tag{16}$$

where b is the base of the triangle. To express A_d in terms of the angle of the submerged corner ϕ and the depth d, we have

$$\tan\frac{\phi}{2} = \frac{\frac{b}{2}}{d}, \tag{17}$$

so

$$b = 2d\tan\frac{\phi}{2} \tag{18}$$

and

$$A_d = \frac{1}{2}\left(2d\tan\frac{\phi}{2}\right)d = d^2\tan\frac{\phi}{2}. \tag{19}$$

Next, we perturb the depth away from nominal by

$$A_{d+\Delta d} = (d+\Delta d)^2\tan\frac{\phi}{2} \tag{20}$$

so that

$$A_{d+\Delta d} - A_d = \left(2d\Delta d + (\Delta d)^2\right)\tan\frac{\phi}{2}. \tag{21}$$

Finally,

$$\begin{aligned} F_B(d+\Delta d) - F_B(d) &= \left[V_{imm}(d+\Delta d) - V_{imm}(d)\right]\rho g, \\ &= l\left[A_{d+\Delta d} - A_d\right]\rho g, \\ &= l\left(2d\Delta d + (\Delta d)^2\right)\tan\frac{\phi}{2}\rho g, \end{aligned} \tag{22}$$

where l is the length of the float, ϕ is the angle of the submerged corner, ρ is the density of water, and g is the acceleration due to gravity. Now, the feedback term depends on the nominal depth d and has a quadratic component.

Finally, we come to the most likely float shape for a traditional outrigger, namely, a circular cross section. In this case, we calculate the area of the submerged segment as a function of the radius r and the depth d given by

$$A_{\text{segment}}(r,d) = r^2\,\mathrm{Cos}^{-1}\frac{r-d}{r} - (r-d)\sqrt{2rd-d^2}. \tag{23}$$

When the float rises out of the water, we see that as $d \longrightarrow 0$, both the first and second terms tend to zero. The buoyant force is thus

$$F_B(r,d) = l\left[r^2\,\mathrm{Cos}^{-1}\frac{r-d}{r} - (r-d)\sqrt{2rd-d^2}\right]\rho g. \tag{24}$$

If we consider d to be the equilibrium depth for a given float material and radius, then the force opposing any displacement Δd is

$$\begin{aligned} &F_B(r,d+\Delta d) - F_B(r,d) \\ &= l\Bigg[\Bigg(r^2\,\mathrm{Cos}^{-1}\frac{r-(d+\Delta d)}{r} - (r-(d+\Delta d)) \\ &\qquad \times\sqrt{2r(d+\Delta d)-(d+\Delta d)^2}\Bigg) \\ &\qquad - \left(r^2\,\mathrm{Cos}^{-1}\frac{r-d}{r} - (r-d)\times\sqrt{2rd-d^2}\right)\Bigg]\rho g. \end{aligned} \tag{25}$$

For small Δd, (22) and (25) become linear in Δd, which matches physical intuition.

most of the year in the South Pacific. Based on this dismissal of the Polynesian craft, Heyerdahl proposed that Southern Polynesia was settled from South America, whereas Hawaii was settled by Northwest Pacific Coast Native Americans, who had originally arrived at the Vancouver Archipelago in double canoes from Asia by way of the Humbolt current [8]. According to Heyerdahl, these Northwest Native Americans followed the same currents traveled by Oregon pines that fell into the ocean and drifted to Hawaii. Heyerdahl's theory was popularized by the experimental voyage of the Kon Tiki, a balsa wood raft that Heyerdahl and his crew sailed from South America to Polynesia, mainly by drifting on the prevailing currents. Since the archaeological evidence supported migration from Asia, Heyerdahl's theories found little scientific support [9].

Figure 12. *Mural depicting an ancient Polynesian double-hull voyaging canoe. This mural hangs in the lobby of the Outrigger Waikiki Hotel. The general lore [7] that Polynesians traveled across the Pacific for purposeful exploration is now accepted as fact [9], [12].*

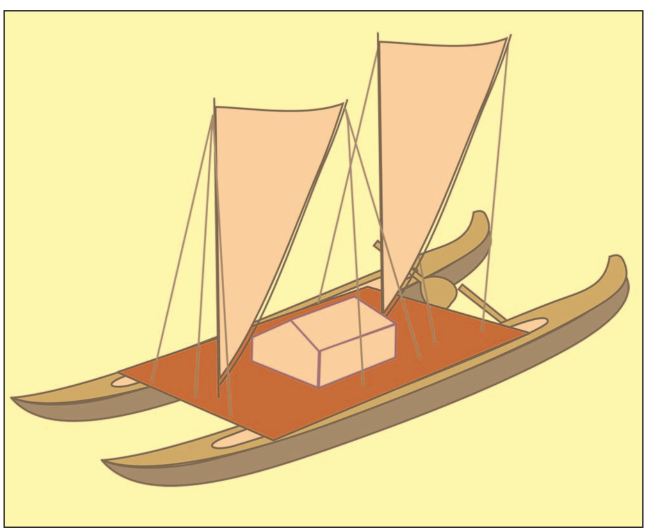

Figure 13. *Double-hull Polynesian voyaging canoe. Traditional double-hull canoes were made entirely from materials available from soft tropical trees. These materials lack the strength of modern boat-making materials such as steel, aluminum, and fiberglass, and limit the boat width compared with the double-hull canoe's modern descendant, the catamaran.*

Andrew Sharp launched a different attack on the traditional theories. While he accepted Polynesian migration from Asia, Sharp claimed that the Polynesian craft and sailing methods were too crude for anything beyond accidental migration. He proposed that the islands of Polynesia were settled by fishermen whose boats got caught in storms and drifted to new islands. Sharp dismissed theories and stories of intentional Polynesian exploration as "romantic nonsense" [10]. However, simulation studies have shown that the probability of success with accidental migration was infinitesimally small [11]. Furthermore, Polynesians on a fishing expedition were unlikely to have with them the supplies (such as livestock and food plants) needed to settle a new island. Finally, since ocean fishing was primarily the work of Polynesian men, there would be no women on these boats. Thus, any island accidentally settled by fishermen would end up having only one generation of inhabitants.

To counter Sharp and Heyerdahl's respective theories, a team led by Ben Finney at the University of California in Santa Barbara built a traditional Polynesian double-hull canoe (shown in a mural in Figure 12 and in a simple drawing in Figure 13) and sailed the canoe between Hawaii and Tahiti using traditional Polynesian seafaring methods. The voyages of the Hokule`a [9], [12], shown in Figure 14, proved that traditionally built and navigated Polynesian double-hulled canoes were capable of voyaging long distances against the wind to find remote islands. The boats proved extremely seaworthy, demonstrating good stability and speed as well as the ability to sail close to the wind. Thus, the underlying premise of Sharp and Heyerdahl's theories were invalidated. Finney also pointed out that the sort of "Kamikaze migration"

KĀIULANI MURPHY

Figure 14. *The double-hull Polynesian voyaging canoe Hokule`a. This vessel was built in a traditional design using modern materials. The ship is navigated using traditional Polynesian methods. Its home berth is in Oahu, Hawaii.*

suggested by Sharp and Heyerdahl was not logical. If one explores by sailing *with* the prevailing wind and current, then returning home is a real challenge. However, by initially sailing against the wind and current for exploration, then it is relatively easy to turn around and head home. The explorers can simply explore into the wind and current until half their supplies are gone. At that point, turning around and sailing with the wind and current should allow the crew to return home easily. The latter method seems much more likely to ensure the survival of the explorers.

Today, there is little debate that Polynesians are descended from the Austronesian peoples. The archaeological evidence suggests that Austronesians migrated from Southeast Asia sometime between 40,000 and 30,000 years ago. This migration was during the last ice age of the Pleistocene era, which began 70,000 years ago and ended 10,000 years ago [13], [14]. During this ice age, the ocean levels were lower than they are today, implying that the crossing from Asia to New Guinea was possible with trips of under 30 miles over shallow and calm seas. On these trips, the destination island would have been visible from the starting point, and so it is not obvious that much seaworthiness was required of the watercraft. However, traveling from the Huon Peninsula on the eastern coast of New Guinea (where 40,000-year-old tools were found) to New Ireland (where 32,000-year-old remains have been found) required crossing deep straits and, therefore, necessitated seaworthy craft. Even more dramatic would be traveling between New Britain and New Ireland to the next island, Buka, in the northern Solomon Islands (see Figure 15). The voyage to Buka required an open-water crossing of 100 miles, and the archaeological evidence reveals human remains dating back as early as 28,000 years ago [15]. The Austronesians started moving out into the Pacific islands 3,500 years ago, reaching the Bismarck Archipelago by 1500 BC, and island hopping all the way to Samoa by 1000 BC [16]. Each leg of this migration required open ocean trips of hundreds of miles, far out of sight of land. The lack of seaworthiness of dugout canoes, due to their stability problems, implies that outrigger technology, either in the form of outrigger canoes or double-hulled canoes, made this trek possible. Hence, the *minimum* age of outrigger technology is 3,500 years. If the outrigger were associated with the migration to Australia,

Figure 15. *Papua, New Guinea, and the Solomon Islands. This map shows New Guinea, New Britain, New Ireland, and Buka Island, where evidence of human settlement has been found. The Huon Peninsula in New Guinea (A) holds remains of 40,000-year-old tools. The crossing from New Guinea to New Britain (B) and New Ireland (C) must be made over deep channels, but both starting point and destination are in view at all times. New Ireland (C) shows evidence of human settlement 32,000 years ago. The channel between New Ireland and Buka Island was deep and over 100 miles wide in the Pleistocene era. Buka Island shows evidence of human settlement 28,000 years ago. Thus, the voyage from New Ireland to Buka Island would have required seaworthy craft. Courtesy of the University of Texas Libraries, the University of Texas at Austin [25].*

New Britain, New Ireland, and Buka, the technology would be considerably older [15].

Additional evidence concerning the origin of the outrigger is associated with migration from Asia to Polynesia. The Polynesians used both outrigger canoes (Figure 16) and double-hull canoes, the latter being the primary vessel for long-range exploration [12]. As stated by Finney:

> Polynesian culture developed not in any Asian or American homeland, but in Polynesia itself. Seafarers ancestral to the Polynesians moved from eastern Melanesia to the uninhabited islands of Tonga and Samoa between 1500 and 100 BC. They settled there, and over the centuries the basic Polynesian cultural pattern developed. Starting about the time of Christ, seafarers, full-fledged Polynesians now, moved from these western Polynesia centers to the east to settle first probably the Marquesas Islands and then the Society Islands (the most important of which is Tahiti). [12]

Stanley also places the origins of Polynesian migration at around 1500–1600 BC:

> Sometime after about 1600 BC, broad-nosed, light-skinned Austronesian peoples entered the Pacific from Indonesia or the Philippines. . . . Three thousand five hundred years ago, the early Polynesians set out from Southeast Asia on a migratory trek that would lead them to make the "many islands" of Polynesia their home. Great voyagers, they sailed their huge double-hulled canoes far and wide, steering with huge paddles and pandanus sails. To navigate they read the sun, stars, currents, swells, winds, clouds, and birds. Sailing purposefully, against the prevailing winds and currents, the Lapita peoples reached the Bismarck Archipelago by 1500 BC, Tonga (via Fiji) by 1300 BC, and Samoa by 1000 BC. Around the time of Christ they pushed out from this primeval area, remembered as Havaiki, into the eastern half of the Pacific. [16]

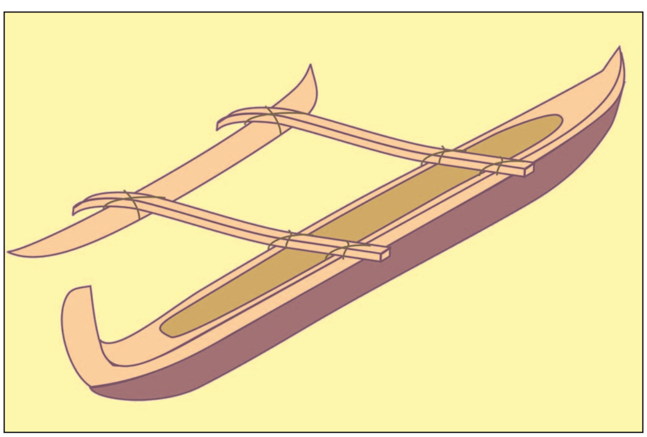

Figure 16. *Hawaiian-style single-outrigger canoe. The single-outrigger design is easier to build than a double-hull canoe, which requires two large matching tree trunks. Having two main hulls that do not match results in differential drag. The outrigger float's drag is considerably less than that of the main hull and thus affects the control of the boat less than having two unequally sized main hulls.*

Given the probable origins of the outrigger in Southeast Asia and the timing of the migrations into the Pacific, we can establish that the outrigger likely dates to at least 1500 BC, 1,200 years before the the water clock of Ktesibios.

Note that the use of the outrigger spanned most of the Pacific and Indian Oceans, from Easter Island and Hawaii in the east to Madagascar in the west. Madagascar was first settled by Indonesians who crossed the Indian ocean in outrigger canoes approximately 2,000 years ago [2]. To the east, the primary Polynesian exploration vessel was the double-hulled canoe, ancestor to the modern catamaran [12]. The single-outrigger canoe was a technology that the Polynesians brought with them for their smaller craft. The outrigger provided equivalent roll stability for a canoe made of only one large log.

Heyerdahl distinguishes different types of outrigger canoes:

> All through Indonesia, from Sumatra and the Philippines to the nearest tip of New Guinea, the

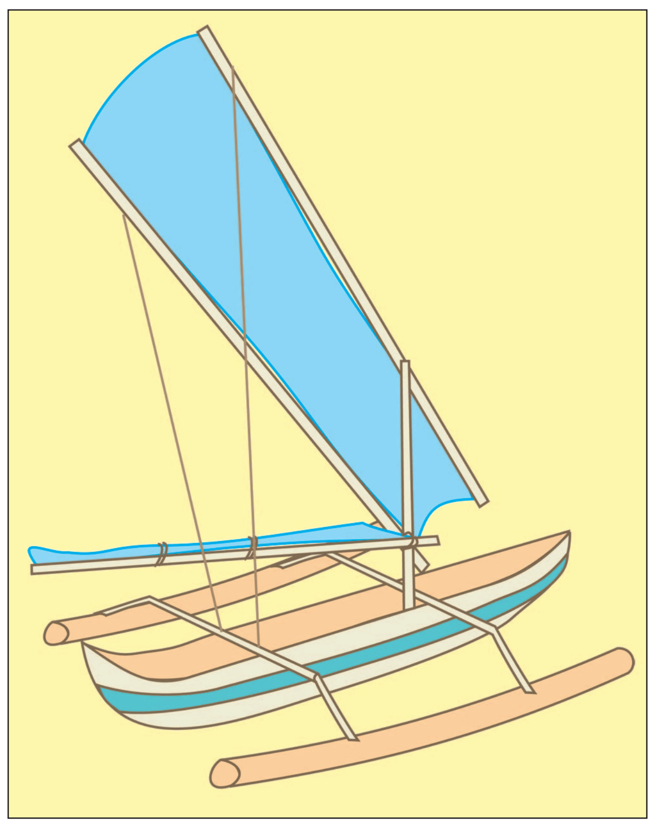

Figure 17. *Double-outrigger canoe of the type found in Indonesia. This drawing is based on images in [18]. Unlike the single outrigger, the double outrigger provides a symmetric righting moment.*

Malays and Indonesians have since early times used the *double* outrigger to stabilize their craft, i.e., a buoyant boom fastened to crossbars on each side of the vessel. The Micronesians and the Melanesians used a *single* outrigger, that is on one side only, and for this reason the Micronesians built their canoes laterally asymmetrical. When the Polynesians adopted the single outrigger on their bilaterally *symmetrical* canoes they did not follow the Micronesian model but followed that of neighboring Fiji. In short, neither the Indonesian nor the Micronesian type of outrigger canoe reached the East Pacific. [1, pp. 160–161]

Where each style of outrigger first appeared is a matter of some debate. Much of the source material on outrigger canoes comes from the work of James Hornell, an official who worked in British India in the early part of the 20th century. Hornell's joint work with A.C. Haddon [17] remains the definitive source for research in this area. Many of the boats documented in the three volumes of *Canoes of Oceania* no longer exist since the book was written in the 1940s. After his retirement, Hornell traveled the world to document the development of watercraft [2]. Although there has been more recent work on the subject, the source material often includes Hornell and Haddon's work because the disappearance of many of these watercraft in the past 100 years has made these books the main documentation available on these vessels. One of the more recent studies was done by Doran [6], who looked at the same source evidence with more modern methods and came to different conclusions about the relative ages of different outriggers. The next section discusses Hornell's view of the origin of the outrigger, and the following subsequent section presents Doran's view on the same topic.

Hornell's View of Outrigger Origins

Hornell's work has put Indonesia as the center of dispersal of the outrigger [2, pp. 263–269]. However, he points out that virtually all watercraft technology originated in rivers and marshes rather than in the ocean [2, pp. 264–265]. Indonesia, lacking significant lakes and rivers, is therefore a poor candidate for the birthplace of the outrigger canoe. Evidence shows that the settlers of Indonesia migrated from Southeast Asia, and it is this region, with its wide rivers, that is most likely the cradle of the outrigger canoe. Hornell suggests that the Irrawaddy, Salween, and Mekong rivers, which "have been from time immemorial the only highways of migration available to the peoples pressing southwards from the cold

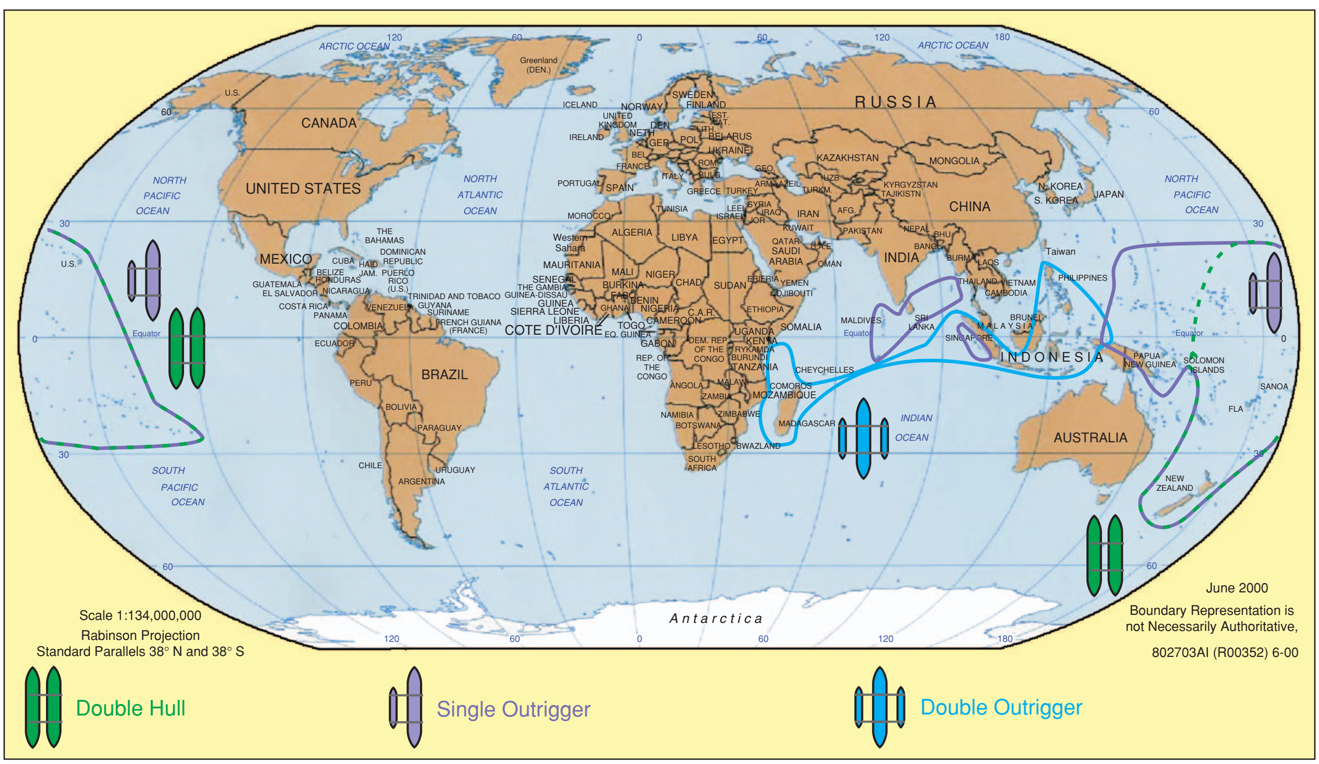

Figure 18. *The distribution of outrigger canoes across the world. This map shows the extent to which each of the different outrigger technologies has spread around the world. The broader distribution of single outriggers compared to double outriggers has been documented in Hornell's research. This research has been interpreted in [6] to suggest that single outriggers are older than double outriggers, and in [2] to suggest that double outriggers are older than single outriggers. The distribution data are merged from maps in [2] and [6]. Courtesy of the University of Texas Libraries, the University of Texas at Austin [25].*

and dreary mountain lands of the north to the fertile lower plains,'' are the likely locations.

> Nowhere else can the development of the dugout canoe into sailing ships of large size be so clearly traceable, step by step, as on the great Burmese river. The dugout in general use by the river people, scattered in innumerable villages along its banks, is the most beautiful of its class. Hewn by men possessed of unconscious skill and inborn artistic feeling, the huge teak baulk is fashioned into a long and relatively narrow craft sheering upwards in a graceful curve toward each end, where it rises well above the water line like the horns of a gigantic crescent. [2, p. 265]

Hornell concludes that the original outrigger craft was a double outrigger [Figure 5(b)] with bamboo trunks for floats [2, p. 266].

From these rivers, the migration to Indonesia was made by watercraft. Thus, for the outrigger to appear in Indonesia, it must have been used in the migration from Southeast Asia. Heyerdahl indicates [8, p. 64] that "outriggers [were] used on local proas in Southeast Asia since the second millennium BC." (A proa is a type of Asian boat.)

The canoes of Indonesia typically have double outriggers, that is, they have an outrigger on each side of the canoe [2]. The double outrigger is diagrammed in Figure 17, based on images from Adrian Horridge's book [18]. Hornell attributes this design to the relatively sheltered waters of the Indonesian archipelago. As outriggers moved into more open water, the single outrigger was structurally safer. Specifically, the double outrigger can suspend the main hull from the outriggers in heavy seas, causing tremendous strain on, and possible breakage of, the crossbars holding the outrigger boom to the main hull. For this reason, Hornell concludes that double outriggers are less seaworthy than single outriggers.

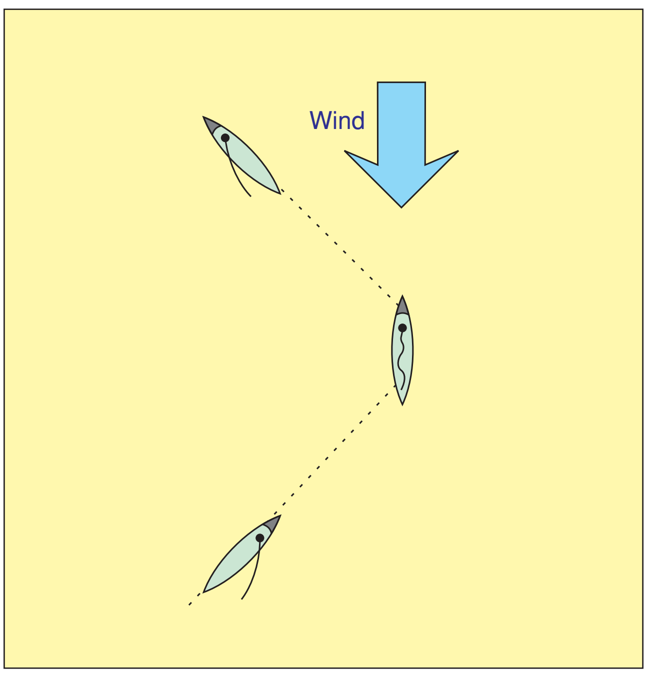

Figure 19. *Sailing into the wind by means of tacking. While all sailboats sail at an angle into the wind, taking a zigzag path forward, the different styles have different methods of turning. Tacking, used by modern sailboats such as sloops, involves swinging the sail around through a null point where the boat is straight into the wind and the sail generates no force on the ship. (These drawings are based on [24, p. 254].)*

Doran's View of Outrigger Origins

Doran's work [6] disagrees with Hornell's view of the double outrigger as unseaworthy and rejects the notion that the double outrigger is the earlier version of the technology. Doran bases his analysis on dispersal patterns centered in Indonesia. He claims that the double-hull canoe preceded the single outrigger, which in turn preceded the double outrigger. He claims that Hornell's arguments of double outriggers being less seaworthy than single outriggers are poorly supported by any actual evidence. Instead, the evidence points to the seaworthiness of double outriggers, as they spread into areas where single outriggers were already present.

Doran makes the case that the geographic extent of double outrigger canoes, being a subset of the geographic extent of single-outrigger canoes, indicates that the double outrigger is a later technology emanating from the center of invention (see Figure 18). Likewise, Doran notes that the practice of shunting when sailing into the wind, as used in Micronesian single-outrigger canoes under sail, is a later development than tacking with a single outrigger. This theory is based on the geographic extent of this practice, which is much smaller than that of single outriggers, but larger than the geographic extent of boats using double outriggers.

Conclusions

When fully considered, outrigger technology, whether used as a single outrigger, double outrigger, or a double-hulled canoe, is truly remarkable. By solving the problem of roll stability for dugout canoes, dramatically increasing the seaworthiness of these craft, the outrigger allowed the Austronesian people to cross the vast reaches of the Pacific and Indian Oceans. This feat was accomplished in a Stone Age culture with no written language, no metal working, and no plank-built boats. As a best estimate, this feedback mechanism predates the water clock by at least 1,200 years. Furthermore, while the water clock was an interesting exercise, this mechanism did not achieve broad penetration into society as a timekeeping device. That task was achieved much later by the mechanical clock in the thirteenth century [19], [20]. The outrigger, on the other hand,

Sailing into the Wind—Shunting Versus Tacking

Among the more interesting features of outrigger canoes are the different ways in which these canoes sail into the wind. While a sailboat cannot sail into the wind directly, some sailboats can sail close to the wind, that is, at a diagonal angle into the wind. The issue then becomes one of how to turn the boat to follow the opposite diagonal as one works against the wind. On a modern sailboat, such as a sloop, the boat progresses against the wind by tacking (Figure 19). In this case, the bow of the boat is always angled into the wind. When the boat turns, the sail goes slack as the boom swings to the other side and the wind fills the sail again. This technique does not work for a square rigger, which at some point in a tack would end up with its sails pushed backward by the direct wind. Instead, square riggers are turned by a looping method known as wearing (Figure 20).

Although most outrigger canoes sail against the wind by tacking, some outrigger canoes employ shunting (Figure 21). To keep the outrigger on the windward side, the Micronesians sail in one direction and then pull to a stop. Since the sailors do not want the outrigger on the leeward (away from the wind) side, they change the position of the sail so that the stern becomes the bow (longitudinally symmetric boat) and then they zag back in the new direction. Having the outrigger on the leeward side could cause the outrigger float to plow into the ocean and capsize as a result of the dynamic behavior of the outrigger in the water. While statically buoyant, an outrigger nosing into the water when the boat is moving can act as a dive-plane on a submarine, pushing that side of the boat further into the water. Thus, the wind can produce a bias force that pushes the system out of its stable zone and into a positive feedback situation. The Micronesians shunt to stay in the negative feedback region [24]. Shunting also keeps the drag on the outrigger from increasing dramatically.

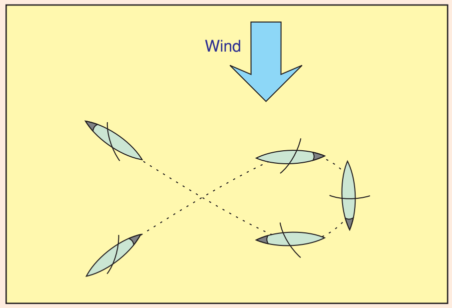

Figure 20. *Sailing into the wind by means of wearing. Square riggers cannot tack (Figure 19) since passing through this null point results in the wind pushing the sails back. Instead, square riggers use a looping turn known as wearing in which the boat never faces directly into the wind. (The drawings are based on [24, p. 254].)*

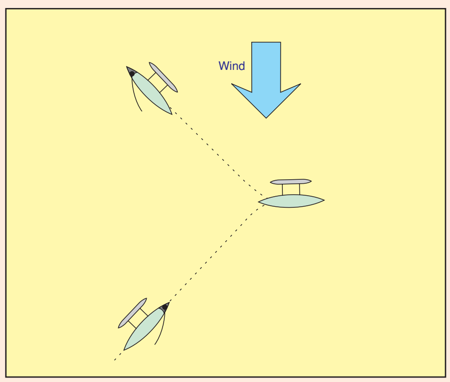

Figure 21. *Sailing into the wind by means of shunting. Shunting is used in some outrigger canoes. In shunting, the turn is accomplished by bringing the boat completely perpendicular to the wind, shifting the mast from one end of the boat to the other, and resuming travel. The advantage of this method is that the outrigger can remain on the windward side of the boat, avoiding the situation in which the outrigger is driven completely into the water. (The drawings are based on [24, p. 254].)*

In tacking, the bow and stern retain their roles while the windward and leeward sides alternate with every direction change. In the case of shunting, the bow becomes the stern and the stern becomes the bow. To accomplish this, the shunters physically move the mast. Thus, the windward side and the leeward side never change.

Shunting is a relatively recent addition to the repository of sailing techniques. In fact, Doran states that shunting is used by Micronesians [6] but not by Polynesians, even though both use a single-outrigger configuration. Malaysians use double outriggers, which makes shunting useless. Likewise, double canoes, forebearers of modern catamarans, simply tack [6], [12].

by dramatically increasing the seaworthiness of the Austronesian canoes, contributed to the colonization of islands from Madagascar to Polynesia, and in that respect, to the very existence of the Polynesian people. They are also a lot of fun (see Figure 22).

Acknowledgments

This article would not have existed without the mechanical inquisitiveness of my son DJ. For putting me on this path, and for many other things, I owe him my gratitude and parental amazement. In researching the article, I received a huge amount of help from the research librarians at Agilent Labs. In particular, Ron Rodriguez was tireless in finding extra references and sources for material on this ancient device. I received encouragement and assistance in making this article more intelligible from Carlene Stephens of the National Museum of American History (NMAH). I also appreciate the assistance of Carlene's

Figure 22. *A modern outrigger canoe riding a wave. This ancient technology is still a lot of fun in the modern world. While double-hull canoes have evolved into catamarans, the outrigger canoes live on in sport paddling and for tourist rides. My son Michael is second from the front, and I am behind him.*

colleague, Dr. Paul F. Johnson, Curator of Maritime History at the NMAH, who gave me some excellent pointers to reference materials and Polynesian migration theories. Dr. Richard Baugh of Hewlett-Packard Laboratories, who actually builds Stone Age tools in his garage, and his wife Marcia provided some highly useful references. Dr. Terril Hurst of Hewlett-Packard Laboratories made his usual strong attempt to improve my writing style. I deeply appreciate the support of my management at Agilent Labs for allowing me to represent the Labs with this work. An earlier version of this paper was presented at a special history plenary session of the 2003 IEEE Conference on Decision and Control.

References

[1] T. Heyerdahl, *Early Man and the Ocean: A Search for the Beginnings of Navigation and Seaborne Civilizations.* Garden City, NY: Doubleday, 1979.

[2] J. Hornell, *Water Transport: Origins and Early Evolution.* London: David & Charles, 1970.

[3] O. Mayr, *The Origins of Feedback Control*. Cambridge, MA: MIT Press, 1970.

[4] O. Mayr, "The origins of feedback control," *Sci. Amer.*, vol. 223, no. 4, pp. 110–118, 1970.

[5] N. Wiener, *Cybernetics: Or the Control and Communication in the Animal and the Machine,* 2nd ed. Cambridge, MA: MIT Press, 1965.

[6] E. Doran, *Wangka: Austronesian Canoe Origins*. College Station, TX: Texas A & M Univ. Press, 1981.

[7] P.H. Buck, *Vikings of the Pacific.* Chicago, IL: Univ. of Chicago Press, 1959.

[8] T. Heyerdahl, *American Indians in the Pacific: The Theory Behind the Kon-Tiki Expedition*. London: George Allen & Unwin, 1952.

[9] B.R. Finney, *Voyage of Rediscovery: A Cultural Odyssey Through Polynesia*. Berkeley, CA: Univ. of California Press, 1995.

[10] A. Sharp, *Ancient Voyagers in the Pacific,* 2nd ed. Hammondsworth, Middlesex, UK: Penguin, 1957.

[11] G. Irwin, *The Prehistoric Exploration and Colonization of the Pacific*. Cambridge, UK: Cambridge Univ. Press, 1992.

[12] B.R. Finney, "Voyaging canoes and the settlement of Polynesia," *Science*, vol. 196, no. 4296, pp. 1277–1285, 1977.

[13] Enchanted Learning, *Ice age mammals* [Online]. Available: http://www.enchantedlearning.com/subjects/mammals/Iceagemammals.shtml

[14] National Wildlife Service, *Geology fieldnotes: Ice age* [Online]. Available: http://www2.nature.nps. gov/geology/parks/icag/

[15] B. Fagan, "Outriggers to the outback," *Archaeology*, vol. 43, pp. 16–18, July-Aug. 1990.

[16] D. Stanley, *Moon Handbooks Tahiti—Including Easter Island and the Cooks,* 4th ed. Chico, CA: Moon Publications, 1999.

[17] A.C. Haddon and J. Hornell, *Canoes of Oceania*. Honolulu, HI: Bishop Museum Press, 1975.

[18] A. Horridge, *Outrigger Canoes of Bali and Madura, Indonesia*. Honolulu, HI: Bishop Museum Press, 1987.

[19] D.S. Bernstein, "Feedback control: An invisible thread in the history of technology," *IEEE Contr. Syst. Mag.*, vol. 22, pp. 53–68, Apr. 2002.

[20] O. Mayr, *Authority, Liberty & Automatic Machinery in Early Modern Europe.* Baltimore and London: The Johns Hopkins Univ. Press, 1986.

[21] D.Y. Abramovitch and D.K. Towner, "A re-writable optical disk having reference clock information permanently formed on the disk," US. Patent 6 046 968, Apr. 4, 2000.

[22] D. Abramovitch and G. Franklin, "A brief history of disk drive control," *IEEE Control Syst. Mag.*, vol. 22, pp. 28–42, June 2002.

[23] D. Abramovitch, "The outrigger: A prehistoric feedback mechanism," in *Proc. 42nd IEEE Conf. Decision and Control*, Maui, HI, Dec. 2003, pp. 2000–2009.

[24] B. Cotterell and J. Kamminga, *Mechanics of Pre-Industrial Technology.* Cambridge: Cambridge Univ. Press, 1990.

[25] University of Texas Library Online, World map [Online]. Available: http://www.lib. utexas.edu/maps/

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