Non-trivial Balance of Centrifuge Rotors

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***Abstract*—Loading test tubes in opposite holes and adding the dummy tube are far from being the only ways to balance the centrifuge rotors. The balance can be sought with higher-order symmetrical configurations of tubes, which offer operational advantages, particularly in dealing with tubes of unequal mass. Since higher-order symmetrical configurations are a bit complicated, *centrifugeR* was introduced as a tool to assist centrifuge operators in the adoption of this non-trivial approach.**

***Index Terms*—centrifuge problem; blank tube; prime number; linear combination; rotational symmetry; random sampling**

INTRODUCTION

Centrifuges are essential devices for particle fractionation in biology and medical laboratories. Due to the extreme forces generated during operation, the use of centrifuges requires safety practices to eliminate potential associated hazards [1]. Accordingly, the importance of balancing test tubes in centrifuge rotors has been emphasized in classical texts on centrifugation [2]–[5] as well as in laboratory manuals [6]. Specifically, a rotor is balanced when the center of mass of the test tubes and the center of rotation of the rotor coincide [7], [8]. For widely used fixed-angle rotors with even numbers of equally spaced holes such as 6, 10, and 30, to name but a few, an even number of identical test tubes are conventionally balanced by loading tubes in opposite holes (Fig. 1a). To balance an odd number of test tubes, the common practice [2], [6] is to add a "dummy" tube containing water or the same solution as the test tube(s) as a counterweight (Fig. 2a).

The search for alternative methods to balance the odd numbers of test tubes without using the dummy tube gave rise to the "balanced centrifuge problem" [9]–[11] which originally questions which k identical test tubes can be balanced in an n-hole centrifuge rotor. Sivek [12] proved that the balance is perfectly possible "if and only if both k and $n - k$ are expressible as linear combinations of prime factors of n with nonnegative coefficients". For example, 7 identical test tubes can be balanced in a 30-hole rotor if and only if 7 and 23 can be expressed as a sum of 2, 3, and 5. The involvement of these prime numbers stems from the fact that the configurations of tubes with rotational symmetry of orders 2, 3, and 5 are intrinsically balanced in a 30-hole rotor since their mass centers always coincide with the rotor rotation center (Fig. 1). Consequently, the superimposition of these configurations also maintains the balance (Fig. 2b, c) as long as there is no overlap of test tubes in the same hole, i.e., the exclusion principle [9], [13].

Based on the theorem of Sivek [12], several efforts have been made to find the rotationally symmetrical balance of k tubes in centrifuge rotors, providing one or multiple solution(s) for each valid k [14]–[17]. In fact, the 30-hole rotor supports the symmetrical balance of all possible numbers of tubes except 1 and 29 [14]. Peil and Hauryliuk [13], however, showed that the balance can also be achieved with many asymmetrical configurations of tubes that are seemingly not built upon the tube configurations with rotational symmetry (Fig. 2d). It turns out that the asymmetrical balance of 7 tubes, for example, is merely one possible result of removing 23 tubes with rotationally symmetrical configurations from a fully filled 30-hole rotor. The next section discusses the merits of symmetrical configurations (with or without the dummy tube) and asymmetrical configurations in balancing centrifuge rotors.

THE TRIVIAL, THE PROMISING, AND THE UNNECESSARY

Adding a dummy tube to form the trivial configurations with rotational symmetry of order 2 (Fig. 2a) is the most intuitive approach to balancing the odd numbers of test tubes (Fig. 3). Without the dummy tube, the symmetrical balance of tubes must entail the configurations with rotational symmetry of higher orders (Fig. 2b, c), making it more difficult to grasp. However, what perplexes users the most is the asymmetrical configurations (Fig. 2d), which would require more than mental calculation to verify the balance [13]. Given the high perceived difficulty (Fig. 3), the non-trivial configurations (i.e., asymmetrical and higher-order symmetrical) should only be utilized by well-informed users.

Operationally, preparing a dummy tube of the same mass as a test tube could be time-consuming. The non-trivial configurations obviate the need for the dummy tube and thus are more convenient (Fig. 3). However, the asymmetrical configurations are practically unnecessary since they offer no operational advantage while being overly complicated compared with the higher-order symmetrical configurations. I hold the view that seeking the higher-order symmetrical balance is a promising practice, as explained in the next section.

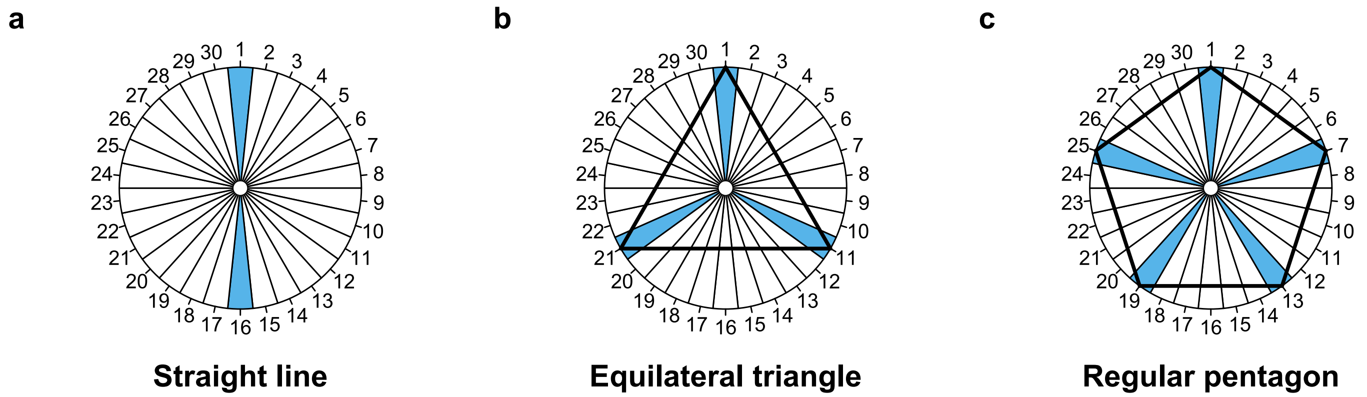

Fig. 1. Balanced configurations of identical test tubes with rotational symmetry of orders 2, 3, and 5 in a 30-hole rotor, forming a straight line, an equilateral triangle, and a regular pentagon, respectively. Filled holes are marked with colors.

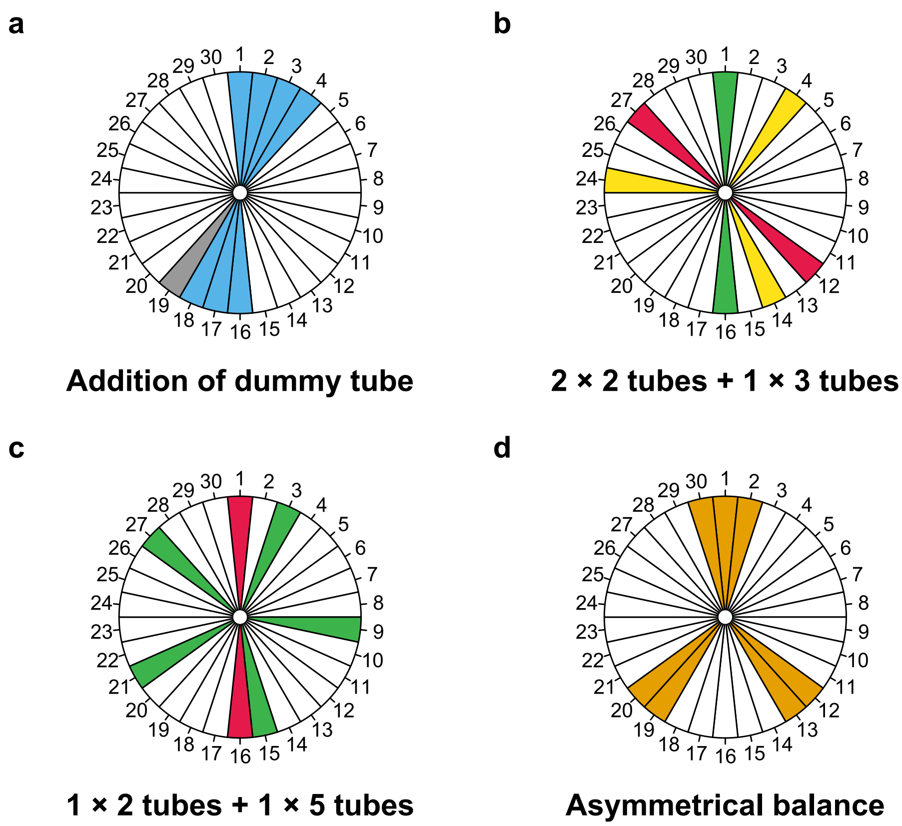

Fig. 2. Three approaches to balance 7 identical test tubes in a 30-hole rotor – adding a dummy tube (hole 19) to create balanced configurations with rotational symmetry of order 2 (a), using balanced configurations with rotational symmetry of higher orders (b, c), and using asymmetrical configurations (d). Filled holes are marked with colors. Holes that form a configuration with rotational symmetry (b, c) share the same color.

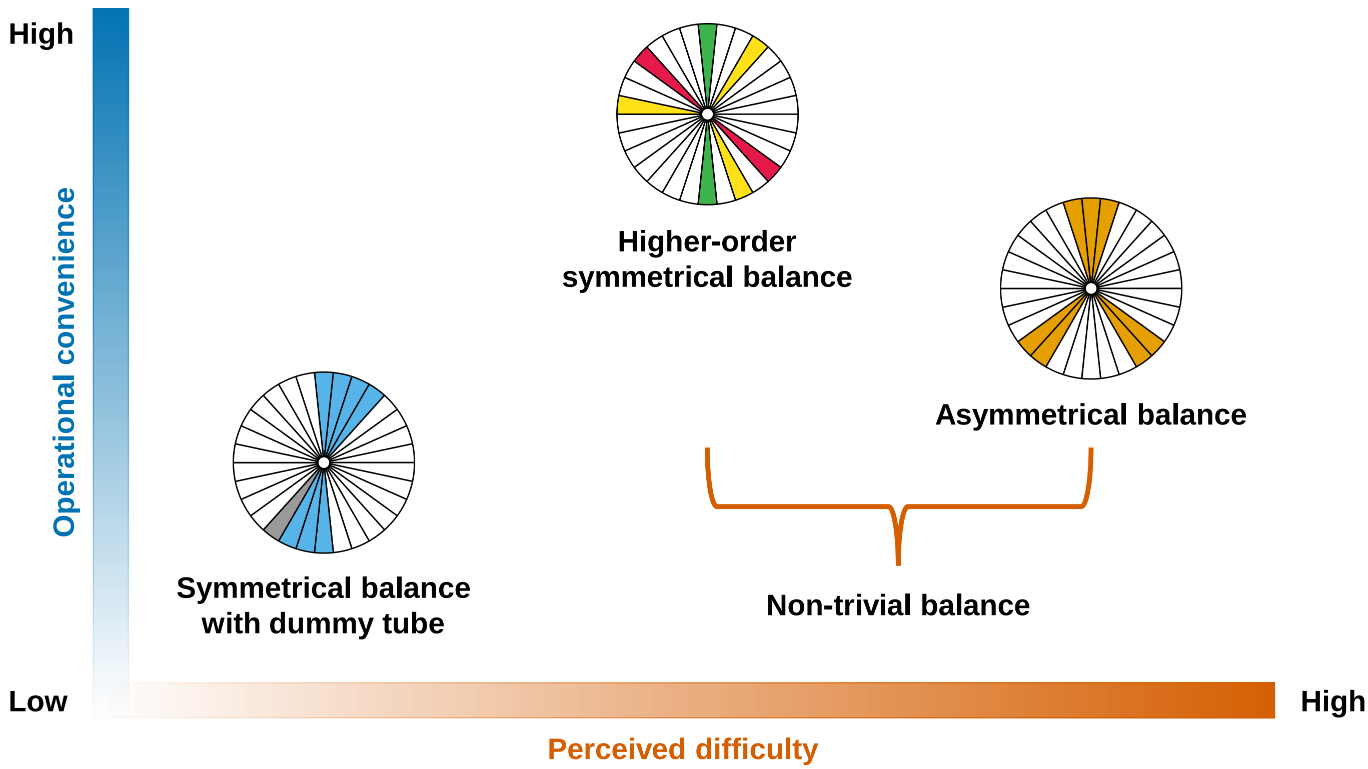

Fig. 3. A comparison of three approaches to balance the odd numbers of identical test tubes in centrifuge rotors in terms of perceived difficulty and operational convenience.

centrifugeR

One possible application of the higher-order symmetrical configurations is the balancing of non-identical test tubes (i.e., tubes of unequal mass). For instance, in the case of 7 tubes in a 30-hole rotor (Fig. 2b), doubling the mass of the three tubes belonging to the equilateral triangle configuration does not alter the center of mass of all 7 tubes. The balance can be sustained as long as the tubes that form a configuration with rotational symmetry have the same mass (Fig. 1). It is worth noting that there is more than one way to split 7 tubes into the sets of 2, 3, or 5 tubes (Fig. 2b, c), giving more flexibility in handling tubes of unequal mass.

Previous works on the rotationally symmetrical balance without the dummy tube [14]–[17], unfortunately, have only focused on determining which rotor holes to be filled to achieve the balance but overlooked the diversity of symmetrical configurations. In 2020, I wrote the R [18] package *centrifugeR* to address this issue. Briefly, *centrifugeR* used simple random sampling to list different ways to express k test tubes as a sum of prime factors of n holes. For example, 19 test tubes in a 30-hole rotor can be decomposed in 9 unique ways (Fig. 4). The mechanics of *centrifugeR* are demonstrated with $n = 30$ and $k = 19$ and summarized in Appendix.

As k increased, more ways of decomposition into prime factors were often expected (Fig. 5). Some of those ways, however, were invalid due to the exclusion principle [9], [13]. For example, 23 can be theoretically expressed as a sum of 2, 3, and 5 in 13 different ways but only 8 of those actually worked in the 30-hole rotor (Fig. 5).

With informative visualizations, *centrifugeR* can help reduce the perceived difficulty of the higher-order symmetrical balance and embrace this practice in balancing centrifuge rotors.

Appendix

Mechanics of *centrifugeR*

Step 1. Find the prime factors p of $n = 30$:

$$p = \{2, 3, 5\}.$$

Step 2. Find the possible coefficients a of each p with $\max(a) = \frac{n}{p}$:

$$a = \begin{cases} \{a_1 \in \mathbb{N} \mid 0 \leq a_1 \leq 15\} & \text{if } p = 2 \\ \{a_2 \in \mathbb{N} \mid 0 \leq a_2 \leq 10\} & \text{if } p = 3 \\ \{a_3 \in \mathbb{N} \mid 0 \leq a_3 \leq 6\} & \text{if } p = 5. \end{cases}$$

Step 3. Compute the values LC of the linear combination of $p_1 = 2$, $p_2 = 3$, and $p_3 = 5$ with coefficients a:

$$LC = a_1p_1 + a_2p_2 + a_3p_3.$$

Step 4. Check if both $k = 19$ and $n - k = 11$ appear in the list of $(15 + 1)(10 + 1)(6 + 1) = 1232$ values of LC. As the answer was yes, return the the sets of coefficients a_1, a_2, and a_3 corresponding to the locations of $k = 19$ in the list (Table I).

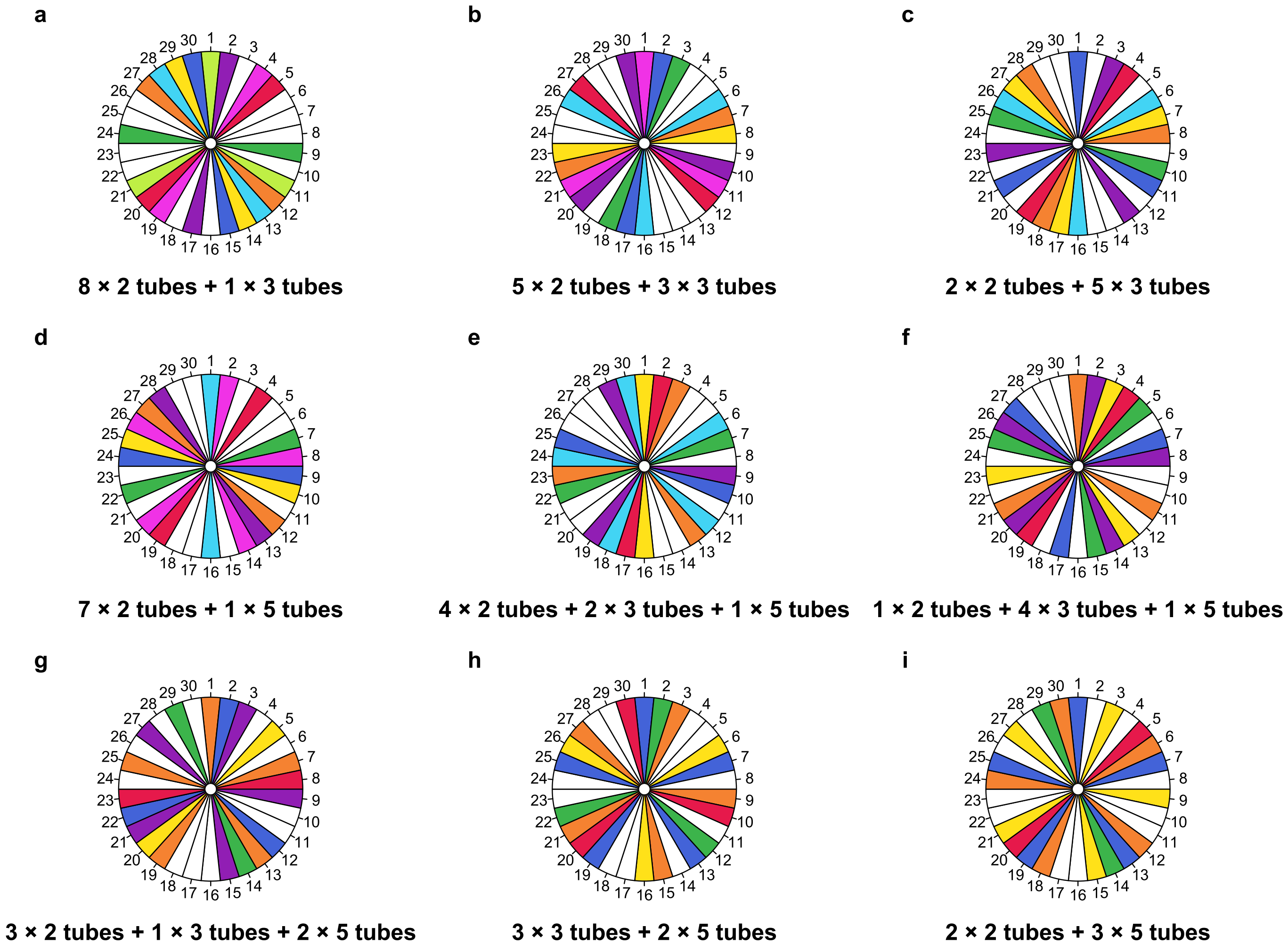

Fig. 4. Nine ways to balance 19 test tubes in a 30-hole rotor by the decomposition into the sets of 2, 3, or 5 tubes, which are advantageous in handling non-identical tubes. Filled holes are marked with colors. Holes that form a configuration with rotational symmetry share the same color.

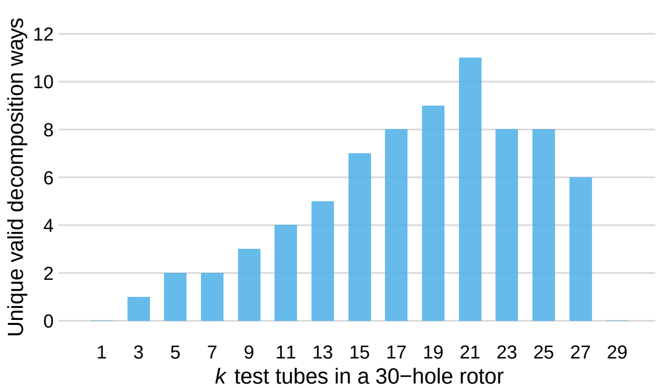

Fig. 5. The number of unique valid ways to decompose the odd numbers of test tubes into the sets of 2, 3, or 5 tubes in a 30-hole rotor.

TABLE I
NINE WAYS TO EXPRESS 19 AS A SUM OF 2, 3, AND 5.

	Location	$p_1 = 2$	$p_2 = 3$	$p_3 = 5$
1	25	8	1	0
2	54	5	3	0
3	83	2	5	0
4	184	7	0	1
5	213	4	2	1
6	242	1	4	1
7	372	3	1	2
8	401	0	3	2
9	531	2	0	3

Step 5. Find the sets of rotor holes that form straight lines, equilateral triangles, and regular pentagons (Fig. 1) corresponding to $p_1 = 2$, $p_2 = 3$, and $p_3 = 5$, respectively:

$$\begin{cases} \{1,16\}, \cdots, \{15,30\} & \text{if } p = 2 \\ \{1,11,21\}, \cdots, \{10,20,30\} & \text{if } p = 3 \\ \{1,7,13,19,25\}, \cdots, \{6,12,18,24,30\} & \text{if } p = 5. \end{cases}$$

Step 6. For each location of $k = 19$, randomly sample without replacement a_1 out of 15 sets of straight line-forming holes, a_2 out of 10 sets of equilateral triangle-forming holes, and a_3 out of 6 sets of regular pentagon-forming holes, e.g., $a_1 = 8$, $a_2 = 1$, and $a_3 = 0$ in the case of location 25 (Table I). Repeat the random sampling process until all 19 obtained holes are different (i.e., no duplicates of holes).

Step 7. Visualize $k = 19$ tubes as the sets of 2, 3, or 5 tubes in centrifuge rotors (Fig. 4).

Competing interests

The author has declared that no competing interests exist.

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Data availability

centrifugeR is publicly available on CRAN at https://cran.r-project.org/package=centrifugeR and on GitHub at https://github.com/phamdn/centrifugeR. A web application is available at https://phamdn.shinyapps.io/centrifugeR/.

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